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NUMERICAL AND GRAPHICAL PROCEDURES FOR ESTIMATION OF COMMUNITY PHOTOSYNTHESIS AND RESPIRATION IN EXPERIMENTAL STREAMS

by

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A numerical dissolved oxygen (D.O.) routing model DORM is developed to determine total stream community photosynthesis (P) and community respiration rates (R) through successive routing of two-station diel D.O. measurements in a stream. The model differs from existing procedures for diel curve productivity analysis in that it uses the complete D.O. transport equation, including D.O. surface exchange, longitudinal dispersion, dependence of respiratory rates on water temperature and dissolved oxygen. The model is applied to the experimental field channels at the USEPA Monticello Ecological Research Station to compute P and R values at different seasons and under different conditions of water temperatures, solar radiation, and pH. A sensitivity analysis shows that computed P and R values are most sensitive to residence times and surface oxygen exchange (reaeration) coefficients. New equations for surface exchange including the effect of wind have been developed and are summarized.

A graphical simplified routing procedure produced P and R values which were 82 and 89 per cent, respectively, of those obtained by complete routing, with a standard deviation of less than 5 per cent. Nighttime longitudinal D.O. gradients were used to derive respiration rates, R.

Maximum values of P and R in the MERS channels were 14.8 g m^{-2} day^{-1} and 10.7 g m^{-2} day^{-1}, respectively. P/R ratios ranged from 0.3 to 2.1. A seasonal dependence of P and R values was found as expected.

Hysteresis in plots of hourly P versus photosynthetically active radiation (PAR) intensity was observed frequently. It was of such magnitude that it could not be caused by errors in surface exchange estimates or other physical processes.

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PREFACE

The research described in this project report was conducted for the USEPA Environmental Research Laboratory, Duluth - Monticello Ecological Research Station. It was initiated in 1978 when the focus of the research program at the Monticello Ecological Research Station (MERS) changed from temperature to toxic substances. The objective was to determine the response of complex freshwater biological systems to stresses caused by pollutants in order to develop criteria for water quality.

The research described herein addressed the need for a tool to measure the functional response of the autotrophic and heterotrophic community to pollutant stresses. The primary goal was to develop a method for the direct measurement (or estimation) of community respiration and photosynthesis in the MERS experimental field channels. To represent the total stream community, a diel dissolved oxygen productivity analysis (Odum, 1956) was chosen.

In this report numerical and graphical routing procedures are described which can be used to derive community photosynthesis and community respiration from two-station diel oxygen measurements. In the process of formulating a complete dissolved oxygen transport equation, a new theory for surface exchange of oxygen was developed and applied to the MERS field channels.

This report summarizes the research. More detailed information on the graphical procedure, the surface oxygen exchange theory, and the numerical results for the MERS field channels can be found in three supplementary external memoranda which are available for purchase from the St. Anthony Falls Hydraulic Laboratory.

1. "Graphical Method to Estimate Stream Community Respiration and Primary Productivity from Stream Dissolved Oxygen Measurements," by Tedd W. Mattke and Heinz G. Stefan, External Memorandum No. 169, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, December, 1980.

2. "Photosynthesis and Respiration Rates in the Monticello Experimental Streams: 1978/79 Diel Field Data and Computed Results," by John S. Gulliver and Heinz G. Stefan, External Memorandum No. 172, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, February, 1981.

3. "Air-Water Surface Exchange of Oxygen: Theory and Application to the USEPA Monticello Experimental Field Channels," by John S. Gulliver and Heniz G. Stefan, External Memorandum No. 173, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, May, 1981.

In addition, the photosynthetic production and the respiratory uptake of oxygen by the planktonic, benthic, and macrophytic components of the biological community in the MERS experimental channels have been described by M. K. Taylor and S. P. Sheldon in "Community Photosynthesis and Respiration in Experimental Channels" to be published in Hydrobiologia, 1981.

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ABSTRACT

A numerical dissolved oxygen (D.O.) routing model DORM is developed to determine total stream community photosynthesis (P) and community respiration rates (R) through successive routing of two-station diel D.O. measurements in a stream. The model differs from existing procedures for diel curve productivity analysis in that it uses the complete D.O. transport equation, including D.O. surface exchange, longitudinal dispersion, dependence of respiratory rates on water temperature and dissolved oxygen. The model is applied to the experimental field channels at the USEPA Monticello Ecological Research Station to compute P and R values at different seasons and under different conditions of water temperatures, solar radiation, and pH. A sensitivity analysis shows that computed P and R values are most sensitive to residence times and surface oxygen exchange (reaeration) coefficients. New equations for surface exchange including the effect of wind have been developed and are summarized.

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SYMBOLS

A	channel cross section area (L^2)
C	dissolved oxygen concentration (M/L^3)
C_{KM}	half saturation coefficient for respiratory inhibition due to low D.O. (M/L^3)
C_s	saturation dissolved oxygen concentration (M/L^3)
D*	dimensionless longitudinal dispersion coefficient
D_L	longitudinal dispersion coefficient (L^2/T)
D_m	molecular diffusivity of dissolved gas in water (L^2/T)
D_{num}	an equivalent numerical longitudinal dispersion coefficient (L^2/T)
F_c	grid flux Courant number $= Q\Delta t/A\Delta x$
J_s	dissolved oxygen surface exchange rate $(M\ L^{-2}\ T^{-1})$
K_2	surface exchange coefficient (T^{-1}) reaeration coefficient
K_s	surface exchange coefficient (L/T) = liquid film coefficient = reaeration coefficient * mean depth
P	total community photosynthetic rate $(M\ L^{-2}\ T^{-1})$
PAR	photosynthetically active radiation $(E\ L^{-2}\ T^{-1})$
Pe	grid Peclet number $= Q\ \Delta x/(A\ D_L)$
Q	rate of change of D.O. per unit water surface area as the water is followed downstream $(M\ L^{-2}\ T^{-1})$
q	rate of change of D.O. per unit volume as the water is followed downstream $(M\ L^{-3})\ T^{-1})$
R	total community respiratory rate $(M\ L^{-2}\ T^{-1})$ or $(M\ L^{-3}\ T^{-1})$

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R_{20}	standard total community respiratory rate at 20°C
Re_s	shear Reynolds number
R_h	hydraulic radius of channel (L)
S	water surface slope
TS	total radiation $(E\ L^{-2}\ T^{-1})$
t	time (T)
t_r	hydraulic residence time of channel reach (T)
U	cross-sectionally averaged flow velocity (L/T)
$u*$	channel bottom shear velocity (L/T)
W	wind velocity (L/T)
x	longitudinal distance channel (L)
z	distance from channel bottom (L)
α	angle between wind direction and stream axis
Δt	time increment (T)
Δx	distance increment (L)
ε	coefficient which specified implicit or explicit character of numerical scheme
θ	temperature coefficient for total community respiratory rate
ϕ	angle of wind to channel (degrees)
ρ	density of water (M/L^3)

UNITS

E	energy
L	length
M	mass
T	time

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SECTION 1

INTRODUCTION

Measurements of dissolved oxygen (D.O.) concentration have often been used to determine primary productivity in streams and lakes. The two basic techniques of productivity analysis from D.O. measurements are the "diel curve" and "isolated chamber" or "light and dark bottle" methods. The isolated chamber method encloses a portion of the water body to estimate component photosynthetic and respiratory rates by changes in D.O. in opaque and clear chambers. The diel curve method utilizes measurements of naturally occurring D.O. fluctuations over a 24 hour period to isolate total community photosynthetic production and respiratory uptake of dissolved oxygen in an open segment of a water body. This method measures productivity by routing D.O. over time and distance in a stream. In D.O. routing, parcels of water are followed along a stream reach, and the changes in D.O. concentration are monitored over a given time period to determine source and sink terms. The change in D.O. concentration which cannot be explained by surface exchange or other external sources is attributed to photosynthetic production and respiratory uptake by the biological community. The first thorough summary of methods for determining primary productivity from D.O. measurements was by Odum (1956). Since then a few variations on Odum's methods have been developed but the majority of the work done in stream productivity analysis still dates back to his original procedures.

The basis for the diel curve method is the conservation of mass principle which can be expressed by an oxygen transport equation. For this study, the unsteady, spatially one-dimensional dissolved oxygen transport equation for a stream is written as

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(D_L\frac{\partial C}{\partial x}\right) + \frac{K_s}{h}(C_s - C) + P - R \qquad (1\text{-}1)$$

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where C = D.O. concentration (cross-sectional mean) (M/L^3),

C_s = saturation D.O. concentration (M/L^3),

= value of C at which no surface exchange occurs,

U = cross-sectionally averaged flow velocity (L/T),

x = longitudinal distance (L),

t = time (T),

h = mean stream depth (L),

D_L = longitudinal dispersion coefficient (L^2/T),

K_s = surface exchange coefficient (L/T),

= liquid film coefficient, $= K_2 * h$

K_2 = reaeration coefficient (T^{-1}),

P = total community photosynthetic rate $(MT^{-1}\ L^{-3})$,

R = total community respiratory rate $(MT^{-1}\ L^{-3})$,

The lefthand side of Eq. 1-1 represents the change in D.O. concentration with time in a water parcel and the downstream advective transport. The first term on the righthand side describes longitudinal dispersion; the second term is the contribution of air/water oxygen exchange (reaeration) to the stream oxygen budget. The community respiration term "R" in Eq. 1-1 includes contributions for sedimentary oxygen demand (SOD), biochemical oxygen demand (BOD), and animal respiration (fish, snails, insects, etc.) in addition to the plant respiration which is primarily of interest. It has to be verified that these other components are insignificant in comparison with plant respiration in order to interprete R correctly.

In a sense, this study was designed to evaluate the limiting assumptions of Odum's (1956) graphical procedure in estimation of community photosynthesis (P) and respiration (R) as applied to experimental streams. It was conducted at the Monticello Ecological Research Station (MERS), U.S. EPA, in outdoor experimental channels. A special effort was devoted to the measurement of meteorological and hydraulic regimes which affect these channels and to provide site-specific estimates of surface oxygen exchange, longitudinal dispersion, and other hydraulic parameters necessary to evaluate oxygen transport therein. A new theory for surface oxygen exchange, including the effect of wind, was developed.

In this study two methods of diel D.O. curve analysis are developed and used to determine total community photosynthesis and respiration in the MERS field channels. The first is a graphical method not much different from Odum's (1956). The second is a computer model DORM (Dissolved Oxygen Routing Model) which includes many aspects of D.O. routing normally neglected in diel D.O. curve analysis of stream productivity. DORM includes surface exchange, longitudinal dispersion, inhibition of respiration due to low D.O. concentration, and dependence of respiratory rate on water temperature. Results from the DORM model are expected to be more accurate than those from the graphical or other methods because the complete oxygen budget equation is used. The results of the two methods are compared and the sensitivity of diel curve analysis to parameter errors is investigated.

REVIEW OF ODUM'S METHOD

Odum (1956) expressed the mass transport equation for dissolved oxygen in a stream as

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} = Q = q/h = P-R+J_s+A \qquad (1\text{-}2)$$

where Q = rate of change of D.O. per unit water surface area as the water is followed downstream (g m^{-2} hr^{-1}),

q = rate of change of D.O. per unit volume as the water is followed downstream (g m^{-3} hr^{-1}),

A = drainage accrual of oxygen from inflowing and outflowing streams, and

J_s = surface exchange per unit water surface area = $K_s(C_s - C)$

Odum suggested several methods to determine P and R in the above equation. One of them is to measure D.O. in a stream over a 24 hour period. It is labeled the "diel (or diurnal) curve method." Two locations on a stream are required when there is any significant gradient of D.O. with respect to longitudinal distance. The two stations provide a means of following any parcel of water through the stream reach over time and, therefore, may be used in dissolved oxygen routing. To determine the source and sink terms, the upstream diel D.O. curve is adjusted in time by the travel time of the study reach. The value of q at various times of the day is found by graphically measuring the difference between the downstream and the shifted upstream diel D.O. curves. If the terms J_s and A have to be determined by separate analysis, then R may be determined from night D.O. measurements and P from measurements of D.O. during daylight hours. One of the main problems is determining surface exchange (J_s).

An example diel D.O. cycle is given in Fig. 1.1. Since D.O. concentration is usually high during the day and low at night, surface exchange is typically a D.O. sink during daylight hours and a source during night hours.

Odum suggested eight methods for estimating surface exchange (J_s). Three of the more applicable are:

a. Dissolved oxygen measurements taken after sunset and just before sunrise may be used to determine the surface exchange coefficient. If a rate of change of D.O., q, is calculated by the above method for morning and evening, and K_s is assumed to be the same in the morning and the evening,

$$K_s = \frac{h(q_M - q_E)}{D_M - D_E} \qquad (1\text{-}3)$$

where q_M = sunrise rate of change of D.O.,
q_E = sunset rate of change of D.O.,
D_M = dissolved oxygen deficit in the morning
$= C_s - C$ for morning, and
D_E = dissolved oxygen deficit in the evening.

b. If R is determined by independent isolated chamber measurements, such as dark bottle or isolated dark cylinders, surface exchange may be calculated from early morning measurements of q_M, when the deficit is largest.

c. If pertinent hydraulic variables such as depth, flow velocity, and water surface slope are known, K_s may be determined from empirical or semi-empirical predictive equations in the literature.

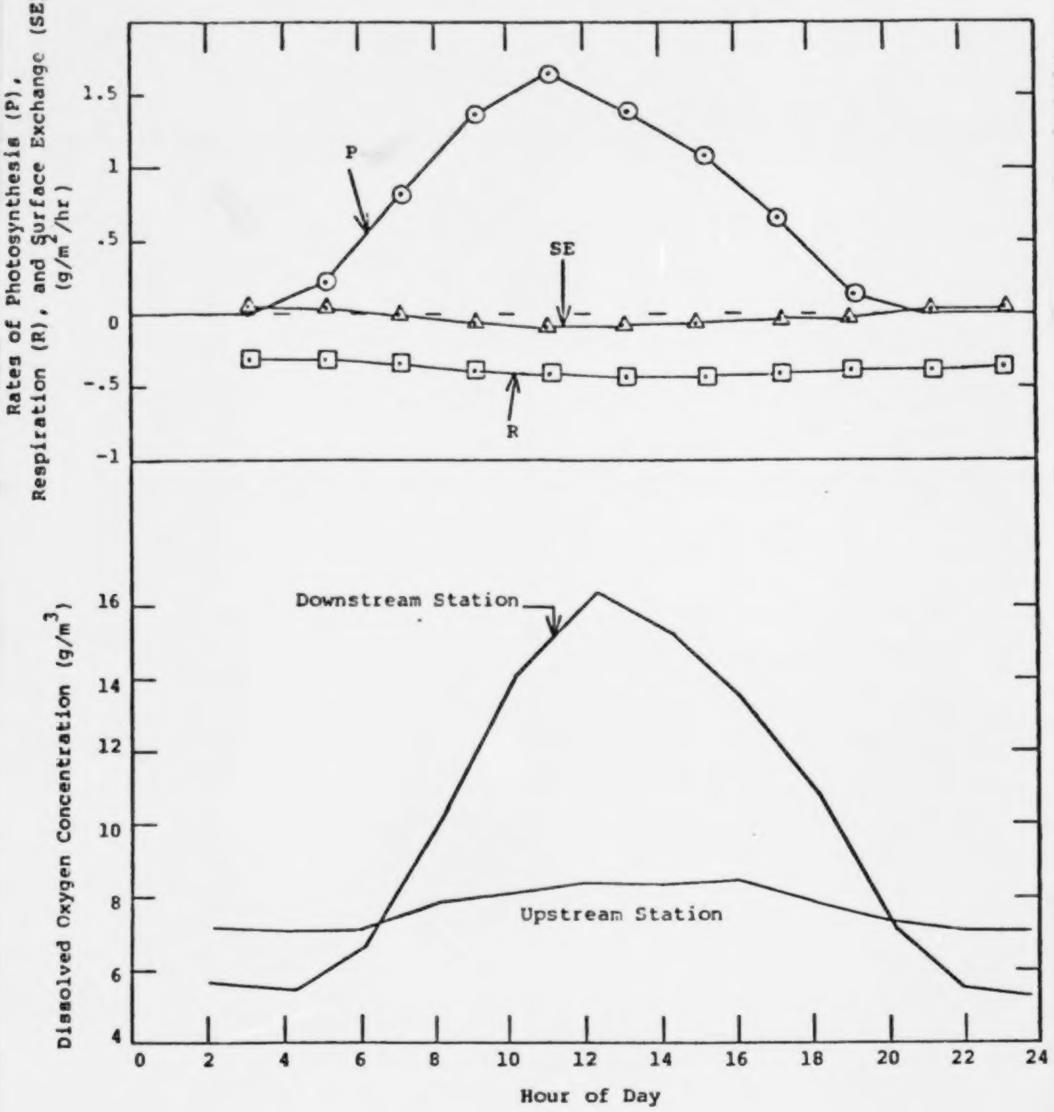

Fig. 1.1. Dissolved oxygen concentrations and resulting photosynthetic, respiratory, and surface exchange rates for field study stream reach.

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With the exception of direct measurements, available methods for estimating surface exchange coefficient for a given stream reach are not reliable. Odum's method (a) has the problem that respiration is not constant but may vary with time of day, water temperature, and D.O. concentration. In many cases the variations in R can be larger than the surface exchange. Independent measurements of total community respiratory rate in isolated chambers suggested for method (b) above are subject to large errors. Enclosing a sample (or samples) which represents the entire community in density as well as structure is very difficult. In addition, the isolated control volume changes many conditions which affect growth such as flow velocity and history of light exposure. Edwards and Owens (1962) noted that "Photosynthetic activity of aquatic macrophytes is related to flow velocity, and estimates made under the quiescent conditions prevailing under bell-jars (isolated chambers) are likely to be erroneous." The errors which occur with independent measurements of respiratory rate are often much larger than the surface exchange rate. With regard to method (c) above, existing equations in the literature are very unreliable for predicting surface exchange coefficient for a given stream reach (Rathbun, 1977; Wilson and MacLeod, 1974; Brown, 1974). An explanation of this problem has been given by Gulliver (1980) and Gulliver and Stefan (1981b).

Estimating surface exchange is still the main unresolved problem in productivity analysis from diel D.O. measurements. It appears that the only way to obtain a reliable surface exchange coefficient is to measure it for the given stream reach. In this study of the MERS field channels a predictive equation with coefficients derived from K_s measurements in those channels is used.

Odum suggests that darkness values of q may be used to find respiratory rate. At saturation, where $D = C_s - C = 0$,

$$R = -q/h + A \qquad (1\text{-}4)$$

and if A is known or is small, R can be found from measurements of q. Equation 1-4 also applies throughout the night period if surface exchange is small with respect to R.

Then, if R is assumed constant throughout the day, total community respiratory rate may be found from

$$P = q/h + R - J_s - A \qquad (1\text{-}5)$$

where R is known, J_s is either known or is small, and A is given. A different value of P would be found for each measurement of q throughout the day.

Odum also suggested that other than two-station D.O. measurements may be used for productivity analysis. If the D.O. concentration in the stream is assumed to be homogeneous with respect to distance, D.O. measurements over a 24 hour period from only one station are needed. In other words, $\partial C/\partial x$ in Eq. 1-2 is assumed to be small. Often data for one station are available and distance homogeneity is assumed whether applicable or not.

Another measurement method is the dye tracer method where a dye tracer is placed in the stream and followed downstream over time. Dissolved oxygen measurements are then taken near the center of the dye cloud over time.

The most successful applications of Odum's method (Edwards and Owens, 1962) have been with measured surface exchange coefficients for the given stream reach. Then total community respiratory rate, R, is determined from nighttime values of q. R is either assumed constant over the day or is given some dependence upon water temperature and D.O. concentration. Finally, using the determined R values, P is calculated at each desired time from Eq. 1-5. There are still two simplifying assumptions to this method; that longitudinal dispersion is not significant and that surface exchange is constant over the stream reach and over time. Both of these assumptions are eliminated by the numerical routing model DORM.

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APPLICATIONS AND VARIATIONS OF ODUM'S METHODS

The majority of stream primary productivity analyses are made with D.O. measurements and by Odum's (1956) methods. Carbon fixation estimates, with carbon-14 labelled carbon dioxide, have been used by Hough (1974) and Hough and Wetzel (1975), and the diel curve method has been applied to CO_2 routing in a stream by Simonsen and Harremöes (1978). Some of the variations on Odum's methods of productivity analysis will be reviewed.

McIntire et al (1964) avoided predicting surface exchange in laboratory streams by covering the streams with black plastic so that no surface exchange would occur and respiratory rate, R , could be estimated from D.O. gradients. Then the difference between q with and without the plastic was interpreted as surface exchange.

Thomas and O'Connell (1966) predicted surface exchange coefficient with the formula given by O'Connor and Dobbins (1958). They also studied photosynthetic production and respiration in dark and light chambers and compared the results to the diel curve method.

Extending Odum's original Eq. 1-2, O'Connor and DiToro (1970) fit the following equation to extensive field data.

$$q/h = \frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{K_s}{h}(C_s - C) + P - R - S - K_d L - K_n N \qquad (1\text{-}6)$$

where S = benthic bacterial respiration rate,

L = carbonaceous BOD,

N = nitrogeneous BOD,

K_d = carbonaceous deoxygenation coefficient, and

K_n = nitrogeneous deoxygenation coefficient.

Photosynthetic rate, P, was included as a Fourier series, L and N were input to the model, and R and S, as well as P, were fit to field data. K_s was predicted with the O'Connor and Dobbins (1958) relationship. The problem was solved by numerically predicting D.O. concentration and varying the fitted coefficients until a good match was achieved. Since

D.O. concentration was predicted numerically, the parameters K_s , L , and N could be functions of time and distance.

Hornberger and Kelly (1972) developed three solutions to the basic equation

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} = \frac{K_s}{h} (C_s - C) + P - R \qquad (1\text{-}7)$$

The solutions included a finite difference method using the complete channel segment as a distance increment, an analytical solution assuming the term P-R to be constant, and an analytical solution assuming linear P-R changes with time. The finite difference technique was unsuccessful because of the large distance increment used. Hornberger and Kelley recommended one of the two analytical solutions for stream productivity analysis.

Kelly et al (1974) fit a Fourier series to D.O. data from two river stations. The continuous Fourier series was then used to analyze stream productivity. The idea behind this method was that Fourier series would fill the short term variations in D.O. concentration and provide more accurate estimates of P and R.

Hornberger and Kelley (1975) used Odum's (1956) method (a) to determine a surface exchange coefficient and devised another method to estimate K_s from curves of P versus total solar radiation (TS). They assumed that P is linearly dependent upon TS. When a hysteresis occurred in the P versus TS curve resulting from diel productivity analysis, it was assumed to be caused by an incorrect value of K_s . K_s was then adjusted until the hysteresis disappeared. To attribute hysteresis in the P versus TS curve solely to surface exchange, however, is arbitrary. There are other possible causes of hysteresis such as discussed in Section 8.

Rutherford (1977) applied a numerical model to diel curve analysis which included a separate equation for BOD and separate D.O. source and sink terms for macrophytes, photoplankton, and periphyton. The source and sink terms were calibrated to field data and then used to predict D.O. concentration over the stream reach. Surface exchange coefficient was estimated by Isaacs and Gaudy's (1968) equation.

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Simonsen and Harremöes (1978) used the diel curve method to study both dissolved oxygen and inorganic carbon production in a stream. They called it the "twin curve method" and found that more information about the photosynthetic production of a stream community was obtained through their method.

Edwards et al (1978) studied stream productivity with the diel curve method in drainage channels which stratified diurnally. Productivity analysis using single and multilayered models gave similar values for total community P and R.

Most recently Erdmann (1979) determined total daily P and R by Odum's (1956) diel curve method and used the determined values as inputs to a steady state predictive dissolved oxygen model. The result was a successful prediction of D.O. concentration even though total daily P values varied highly.

Virtually all of the diel curve D.O. routing methods described herein involve variation in the detail, rather than the substance, of Odum's (1956) diel curve methods. Most variations are in the determination of the surface exchange coefficient. The most accurate diel curve analyses are obtained if K_s is measured directly for the stream study reach. This may be done with gas tracers (Tsivogou et al, 1965, 1968), or by depleting D.O. concentration with sodum sulfite (Edwards et al, 1961) or by night D.O. routing (Gulliver and Stefan, 1981b). For streams in which primary production is dominated by attached periphyton and aquatic macrophytes, the night D.O. routing has proven to be a simple and accurate method of determining surface exchange coefficients. The method may not be applicable to streams with predominantly phytoplankton populations.

As with other work reviewed in this section, the numerical and graphical procedures described herein are also a variation on Odum's original methods. The numerical procedure includes aspects of diel curve analysis which Odum was forced to neglect in his graphical method.

SECTION 2

CONCLUSIONS

1. A numerical Dissolved Oxygen Routing Model (DORM) was developed to determine total stream community photosynthesis (P) and respiratory (R) rates through successive routing of two station diel D.O. measurements. The method is based on the D.O. transport Eq. 1-1. In D.O. routing the change in D.O. concentration between two stations on a stream reach is monitored over a given time period to determine community photosynthesis and respiration. The model includes surface exchange, longitudinal dispersion, a higher order curve interpolation between upstream D.O. measurements, and the dependence of respiratory rate on water temperature and D.O. concentration. Implicit, hybrid finite differences are used in the routing model. The routing involves iterative prediction of downstream D.O. versus time values with increasingly accurate estimates of P (for daytime) and R (for nighttime), until a match of desired accuracy between predicted and measured values is achieved.

2. A theory for surface oxygen exchange (reaeration) in a stream has been developed. The effects of wind and of secondary flows (channel shape) are included. Wind effects are expressed in general form as functions of wind speed, fetch and channel depth. Mixing due to secondary flows is expressed by a parameter which must be measured in a stream reach. The details of this theory and its application to the MERS experimental channels are in an addendum to this report (Gulliver and Stefan, 1981b).

3. A temperature coefficient for total community respiratory rate $\theta = 1.045$ was determined from a sequence of predawn longitudinal

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D.O. surveys in the MERS channels in September 1978 with a temperature range from 15 to 24°C.

4. A half-saturation coefficient for respiratory inhibition at low D.O. concentration, $C_{km} = 2.3\ g/m^3$, was determined from diel D.O. data obtained in a channel reach on three consecutive nights.

5. The potential errors in R and P values for the MERS channels resulting from several simplications of the D.O. transport equation and from inaccurate data input were investigated.

   a. Neglecting surface exchange ($K_2 = 0$) gave substantial reductions of P and R values (typically 8% and 16%, respectively).

   b. Longitudinal dispersion can be neglected for the MERS channels. Only insignificant ($< 2\%$) changes in P and R are produced when hydrodynamic longitudinal dispersion is included.

   c. Using a linear interpolation between upstream D.O. input data collected at two-hour intervals is acceptable. More complete curve fitting to input D.O. data resulted in only minor (0.4%) changes in P and R.

   d. Correct residence times are required. Using incorrect residence times (± 20%) changed P and R values very significantly (± 18%).

   e. Temperature dependence of respiratory rates is of importance in the MERS channels. A diel variation of 5°C results in a 7% change in respiratory rates.

6. Thirty-two diel D.O. surveys encompassing four stream reaches were made at the field study site in late summer and fall of 1978 and spring and summer of 1979. Diel curve productivity was estimated with DORM using data from each survey. Computed R values ranged from $2.6\ g\ m^{-2}\ day^{-1}$ D.O. in October 1978 to $10.7\ g\ m^{-2}\ day^{-1}$ in August 1979 and P values ranged from $1.50\ g\ m^{-2}\ day^{-1}$ in October 1978 to $14.8\ g\ m^{-2}\ day^{-1}$ in June 1979. P/R ratios varied between 0.3 in September 1978 to 2.1 in May 1979.

7. In the MERS channels P/R ratio is a good indicator of community photosynthetic efficiency. Attemps to relate P/R ratios to light

intensity failed because photosynthetic production rates were not linearly related to light intensity.

8. Diel curve analysis was performed in three channel reaches with a respective pH of 8.0, 6.3, and 5.4. The channel reaches with low pH reached maximum total community photosynthetic and respiratory rates earlier in the growing season. This could be due to the lower pH but is more likely attributable to a difference in vegetation history and shading by emergent vegetation in the low pH channel reaches.

9. Total community photosynthetic rates (P) over the day were plotted against photosynthetically active radiation (PAR) for each diel D.O. survey. A direct linear relationship between P and PAR was not observed and hysteresis in the P versus PAR curves was frequent. Counterclockwise hysteresis was observed for three channel reaches on a cloudy day in late July 1979 and a clear day in mid-September 1979. Other surveys in May, June, and August generally gave clockwise hysteresis.

10. Sensitivity analysis of the D.O. routing method indicates that in the MERS channels physical effects alone cannot account fully for the observed hysteresis. Several hypotheses have been proposed to explain the biological causes of hysteresis. Further experimental studies are needed to clarify the relationships.

11. A simplified graphical procedure by which the upstream measured D.O. curve is shifted downstream by the residence time and subtracted from the downstream measured D.O. curve was also applied to the MERS data. The method solves the simplified equation graphically. Of all the processes included in the complete D.O. transport equation 1-1, the graphical method only considers advection, community photosynthesis and community respiration and ignores surface oxygen exchange and longitudinal dispersion. With little scatter, the graphical procedure gave consistent P and R values which were on the average 89 and 82 per cent, respectively, of the values obtained by the complete numerical analysis with DORM. The standard deviation was

± 5 per cent. The P/R ratio given by the graphical procedure was on the average 1.07 times that obtained by the complete DORM with a standard deviation of 0.04. These ratios are valid only for the MERS field channels.

12. Biochemical and sedimentary oxygen demands (BOD and SOD) were measured in the summer in separate experiments in the MERS field channels and were found to have an insignificant effect on computed P and R values.

SECTION 3

RECOMMENDATIONS

Diel curve productivity analysis from D.O. measurements should be undertaken with a numerical routing model such as DORM if a reasonable accuracy in estimates of total community photosynthesis and respiration is desired.

With regard to general diel curve analysis, the following recommendations are made:

1. Field measurements of D.O. should be made in cross sections which are well-mixed. D.O. analysis by the Winkler method is much more reliable than D.O. measurements by sensors and continuous recording. Channel geometry, channel orientation, and flow rates need to be documented with precision.
2. Extreme care should be taken to accurately determine stream reach residence time. This requires precise documentation of channel geometry and flow rates.
3. Surface exchange of oxygen (reaeration) should be measured in the stream reach of interest. Estimates from literature equations are not sufficiently accurate or reliable. Surface exchange in a stream reach may be measured by a method developed by Gulliver and Stefan (1981b) or by other methods reviewed in the same reference.
4. Surface oxygen exchange is often dependent upon wind. Therefore, wind velocity and wind direction need to be measured.
5. Longitudinal dispersion should be included in the diel curve productivity analysis of a highly dispersive system.

6. The temperature dependence of respiratory rates should be included in diel curve analysis when the diel variation in water temperature is 2°C or greater.

7. Respiratory inhibition at low D.O. concentrations should be included in diel curve analysis when D.O. concentrations below 4 g/m^3 are encountered.

8. A linear interpolation between upstream D.O. measurements is acceptable when the data is collected in two-hour intervals. Larger time intervals may require a higher order interpolation.

9. Further investigations should be conducted to investigate the causes of hysteresis in plots of photosynthetic production versus light intensity.

10. Additional research should also be conducted on the D.O. limitation and the effect of temperature on respiration rates (parameters C_{KM}, R_{20}, and θ). Values of θ may vary seasonally. Only late summer data were used to derive a θ value herein.

11. The effects of diurnal stratification on P and R also need further investigation.

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SECTION 4

FIELD STUDY METHODS

DESCRIPTION OF FIELD STUDY SITE

All measurements were undertaken at the Monticello Ecological Research Station (MERS), a field station of the U.S. Environmental Protection Agency's Environmental Research Laboratory in Duluth, Minnesota. The MERS is located approximately 40 miles northwest of Minneapolis, near Monticello, Minnesota, on 34 acres adjacent to a Nuclear Power Generating Plant owned and operated by Northern States Power Company. The MERS has eight soil bottom experimental channels of approximately 520 m (1700 ft) length each. The Mississippi River serves as the main source of water for the channels which operate in a once-through mode. Heat exchangers using waste heat from the power plant can be used to artificially heat the water in any of the channels. The channels are in an elevated area above the Mississippi River and not normally subjected to flooding.

Each of the eight experimental channels at the MERS is approximately 520 m (1700 ft) long, with alternating "pool" and "riffle" sections of approximately 30.5 m (100 ft) length each and one 90 degree bend from an east-west to north-south alignment. There are nine pools and eight riffles in each channel. The approximate geometry of the pool sections is 3.5 m (12 ft) surface width and 0.8 m (3 ft) maximum depth. The pool cross section is approximately parabolic. The riffle sections are contracted areas to increase flow velocity. They are trapezoidal in shape and formed by 1.5 inch gravel placed in the channel. The riffle width at the water surface is approximately 2.0 m (8 ft). Riffles are very shallow, e.g. 0.4 m (15 in.). As the water stage can be controlled by a bulkhead at the end of each channel, the exact water depths and surface widths can also be changed.

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The channels are arranged in pairs, separated by a high berm. There is a gravel road between channel pairs. Figure 4.1 shows one pair of channels. Locations in the channels are numbered, with 1 assigned to the inlet, 2 to the first pool, 3 to the first riffle, etc., up to the outlet which is numbered 19. In addition, each channel was given a number from 1 to 8.

Flow rate in each channel is controlled and metered in the control room of the office building. V-notch weirs are installed at the head (inlet) of each channel and are available for installation at the end of each channel. A more thorough description of physical characteristics for the MERS channels is given by Hahn et al (1978) and Stefan et al (1980).

Diel curve productivity analysis with the Dissolved Oxygen Routing Model (DORM) was performed on various reaches of the MERS field channels. There were two periods of field measurements. The first was in late summer and fall of 1978 when measurements were taken in channel 7 every hour and the time between sampling days was approximately one week. The second period was in the spring and summer of 1979 when eight sampling days were spread over a five-month period. The notation for channel reach indicates the pools and riffles included in that reach. Reach 6-9 includes pools 6 and 8 and riffles 7 and 9. Stream reaches in channels 6, 7, and 8 were studied and measurements were taken every two hours. During this period an artificially low pH was maintained in channels 7 and 8 with acid addition by the MERS staff to study effects on fish and invertebrate growth and reproduction (Zischke et al, 1981).

DISSOLVED OXYGEN MEASUREMENTS

Water samples were taken with a Dissolved Oxygen Sampler at the transition from riffles to pools. Samples were taken at this location because the water was vertically well mixed after travelling through the riffle section and stratification of the water column did not have to be considered. The Dissolved Oxygen Sampler is a stainless steel container which holds two 305 mℓ BOD bottles and flushes 1.5 liters of water through each bottle when submerged. Samples were taken at specified time intervals (~ 2 hours) at the upstream and downstream locations of each study reach. The exact time of measurement for each sample was logged

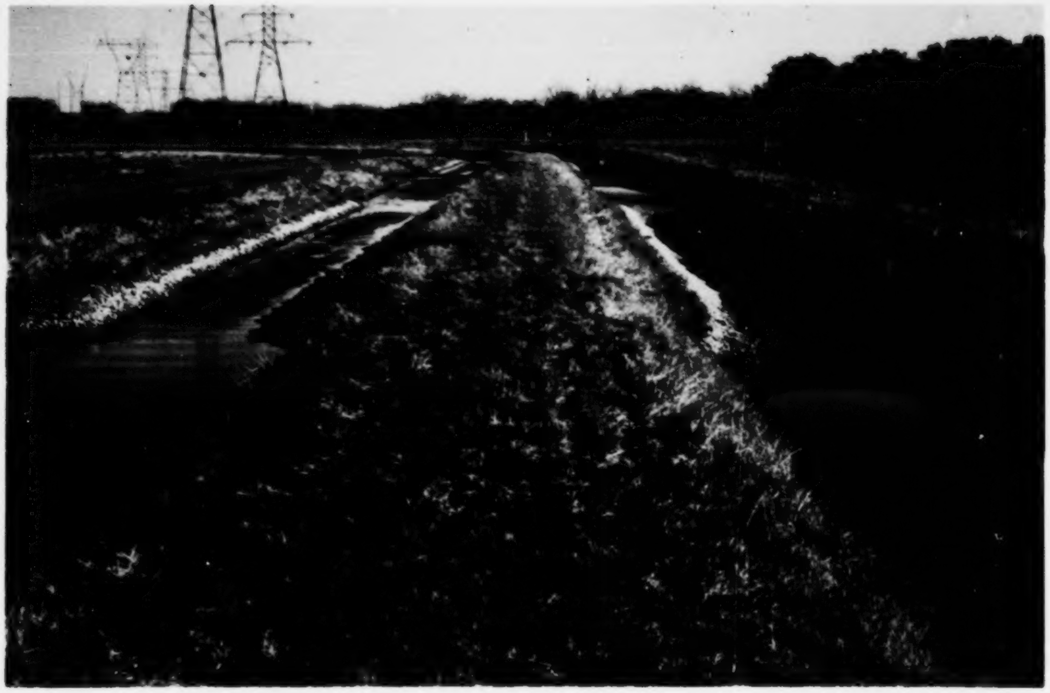

Fig. 4.1. MERS channels showing the transition from pool (foreground) to riffle to pool. The channel on the left is flowing full, while the channel on the right is partially drained, exposing the gravel sides and bottom of the riffle section.

for input into DORM. All samples were fixed in situ and transported to the MERS laboratory where they were analyzed within one hour by Winkler titration (American Public Health Association, 1976).

CHANNEL MORPHOLOGY AND WATER SURFACE SLOPE

The morphologic measurements needed for DORM are cross-sectional area and surface width. These parameters were measured at 3 to 5 locations in each riffle or pool for every stream reach studied. The average values of cross-sectional area and surface width for each pool or riffle are given in Tables 4.1, 4.2, 4.3, and 4.4. Also given in Tables 4.1 through 4.4 are the volume of each pool or riffle and the hydraulic residence time at the average flow rate of .013 m^3/s (200 gpm) throughout the 1979 study period, or the average flow rate of 1026 m^3/s (408 gpm) during the 1978 study period.

During summer months rooted vegetation grows along the edges of both pools and riffles, as shown in Fig. 4.2, to a height of 2 ft or more. This vegetation provides an effective shelter from wind, and reduces the influence of wind on D.O. surface exchange.

Water surface slopes were measured by marking the water surface elevation in the channel at various locations on stakes driven into the bottom of the channels. Then the flow was shut off and the channel outlet was blocked; changes in water surface level between flow and no flow conditions were used to back calculate water surface slope. Due to the acid inflow in channel 7 and 8 the flow could be shut off only in channel 6. During 1979 the hydraulic conditions of these three channels, however, were very similar and the water surface slope measured in channel 6 was applied to channels 7 and 8. Measurements of channel 6 water surface slope in summer 1979 gave 3.05×10^{-4} for channel segments 6 through 13.

During the 1978 study period flow rate and water surface level were both higher than during the 1979 study period. Water surface slopes were also different in the two years. The 1978 water surface slope may be estimated by calculating an average Manning's 'n' value for riffle sections from the 1979 data.

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TABLE 4.1. CHANNEL 7 - CROSS-SECTIONAL MEASUREMENTS, SUMMER, 1978

Station	Cross Sectional Area	Surface Width	Volume	Residence time @ .026 m^3/sec	
	m^2	m	m^3	(min)	(hr)
2	1.20	3.6	36.6	23.7	0.39
3	0.40	2.1	12.2	7.9	0.13
4	1.56	3.6	47.5	30.8	0.51
5	0.49	2.3	14.9	9.7	0.16
6	1.85	3.8	56.4	36.5	0.61
7	0.47	2.3	14.3	9.3	0.16
8	1.64	3.7	50.0	32.5	0.54
9	0.44	2.2	13.4	8.6	0.14
10	1.65	3.4	50.3	32.6	0.54
11	0.38	2.1	11.6	7.5	0.13
12	1.58	3.5	48.2	31.2	0.52
13	0.37	2.1	11.3	7.3	0.12
14	1.65	3.6	50.3	32.6	0.54
15	0.35	2.1	10.7	7.0	0.12
16	1.51	3.4	46.0	29.6	0.49
17	0.26	1.8	7.9	5.1	0.09
18	1.51	3.5	46.0	29.9	0.50

TABLE 4.2. CHANNEL 6 - CROSS-SECTIONAL MEASUREMENTS, SUMMER, 1979

Station	Cross Sectional Area	Surface Width	Volume	Residence time @ .013 m^3/sec	
	m^2	m	m^3	(min)	(hr)
6	1.32	3.4	40.2	53.1	.89
7	0.24	1.7	7.4	9.6	.16
8	1.37	3.2	41.6	54.8	.91
9	0.22	1.7	6.8	8.8	.15
10	1.32	3.0	40.2	53.1	.89
11	0.26	1.6	6.0	7.85	.13
12	1.24	3.3	37.9	50.1	.84
13	0.23	1.8	7.1	9.3	.16

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TABLE 4.3. CHANNEL 7 - CROSS-SECTIONAL MEASUREMENTS, SUMMER, 1979

Station	Cross Sectional Area	Surface Width	Volume	Residence time @ .013 m^3/sec	
	m^2	m	m^3	(min)	(hr)
6	1.26	3.5	38.5	50.1	.85
7	0.19	1.7	5.7	7.5	.12
8	1.25	3.6	38.2	50.5	.84
9	0.14	1.6	4.3	5.6	.09
10	1.21	3.3	36.8	48.6	.81
11	0.20	1.7	6.0	7.9	.13
12	1.12	3.3	34.3	45.3	.75
13	0.11	1.6	3.4	4.5	.07

TABLE 4.4. CHANNEL 8 - CROSS-SECTIONAL MEASUREMENTS, SUMMER, 1979

Station	Cross Sectional Area	Surface Width	Volume	Residence time @ .013 m^3/sec	
	m^2	m	m^3	(min)	(hr)
6	1.47	3.5	44.7	59.1	.98
7	0.28	1.9	8.5	11.2	.19
8	1.59	3.7	48.4	63.9	1.07
9	0.26	1.9	7.9	10.5	.17
10	1.41	3.7	43.0	56.8	.95
11	0.20	1.7	6.2	8.2	.14
12	1.36	3.3	41.3	54.6	.91
13	0.15	1.5	4.5	6.0	.10

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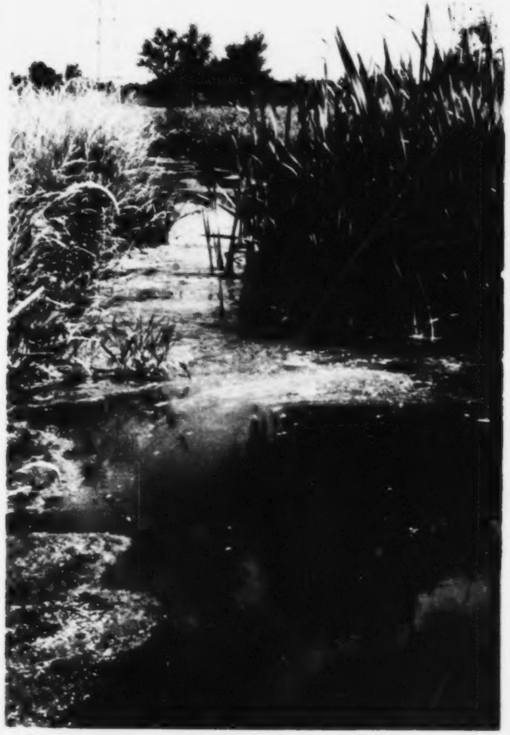

Fig. 4.2a. Example of vegetation growing along the edges of a pool in MERS channel 6, August 1, 1979.

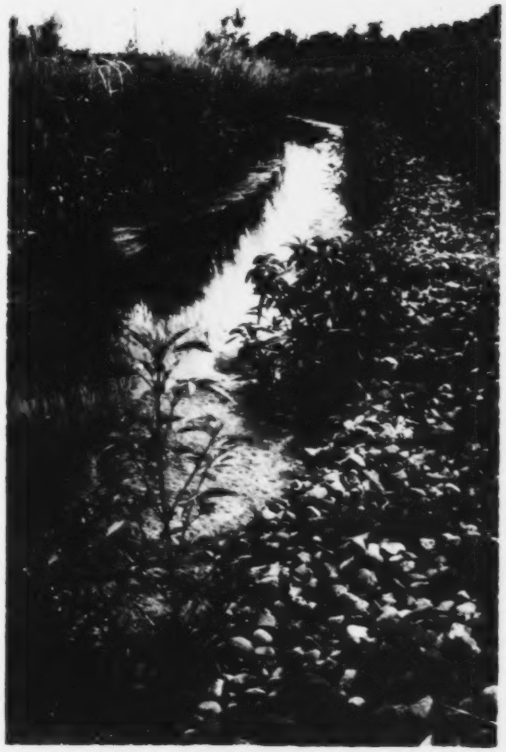

Fig. 4.2b. Example of vegetation growing along the edges of a riffle in MERS channel 6, August 1, 1979.

$$n = \frac{A\ R_h^{2/3}\ S^{1/2}}{Q} \tag{4-1}$$

where R_h = hydraulic radius (m),
S = water surface slope,
A = cross-sectional area (m^2), and
Q = flow rate (m^3/s).

Only riffle sections are included in the parameters of Eq. 4-1 because the bulk of the water surface slope occurs in the riffle sections. Equation 4-1 gives $n = 0.068$ for riffles in channel 6. Applying this n value to channel 7 gives $S = 1.04\times10^{-4}$ for the 1978 study period. Channels 6 and 8 were not included in the 1978 field study.

WATER TEMPERATURE AND pH

During the 1979 study period water temperatures were taken with a hand-held mercury thermometer accurate to 0.1°C at the same time as the water samples. During the 1978 study period water temperatures were measured with a remote thermocouple sensing system controlled by a data logger which recorded water temperature every 15 minutes. The temperature monitoring system is described in detail by Stefan et al (1980).

For their study of pH effects on the aquatic community, the MERS staff introduced a continuous flow of acid into channels 7 and 8 on May 7, 1979. Channel 6 was left in a natural condition at an ambient pH of about 8.0, channel 7 pH was reduced to a target pH = 6.3, and channel 8 was reduced to a target pH = 5.4, measured at riffle 5 in all channels. The pH was controlled and monitored until September 7, 1979, when the acid flow was shut off. Fluctuations of pH over time and channel distance in acid channels 7 and 8 were within ± 0.3 units of the values given above.

SOLAR RADIATION AND WEATHER DATA COLLECTION

Stream primary biological productivity is related to solar radiation. For this reason an Eppley black and white pyranometer model 8-48 was installed 2 m above ground at a weather station near the center of the MERS field channels to measure total solar radiation. The pyranometer is temperature correcting and will give accurate measurements between

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$-20^{\circ}C$ and $40^{\circ}C$. The instrument was individually calibrated before shipment. The pyranometer signal was recorded on a Lintronic voltage-time integrator.

Plants primarily respond to solar radiation in the 400 to 700 nm waveband. Solar radiation within this wavelength region is called photosynthetically active radiation (PAR). To the authors' knowledge, the relationship between total solar radiation (TS) and PAR has not been thoroughly studied. Normally PAR is assumed to be directly proportional to TS; however, the effect of clouds and other atmospheric conditions on this relationship is unknown. For this reason a Lambda 190S quantum sensor was installed to measure PAR. The quantum sensor signal was recorded hourly by a Lambda LI-550 printing integrator.

A comparison of hourly total solar radiation and PAR measurements given in Fig. 4.3 for a number of sunny and cloudy days indicates that the linear relationship is accurate and that one proportionality constant may be applied to both cloudy and sunny days. This relationship may not apply under extreme conditions such as dust storms. In addition, the effect of shade is not included. The data in Fig. 4.3 gives

$$\mathrm{PAR(Einstein/m^2)} = 0.086\ \mathrm{TS(Langley)} \qquad (4\text{-}2)$$

One Einstein is 6.023×10^{23} photons. A Langley is one $\mathrm{cal/cm^2}$.

The other weather parameters required for DORM are wind direction and velocity. Wind velocity was measured at 1.5 m above the water surface with a Belfort counting anemometer. Wind direction was measured at 4 m height with a Texas Electronics wind vane, transmitter, and power supply unit and continuously recorded on a Rustrak recorder (Stefan et al, 1980).

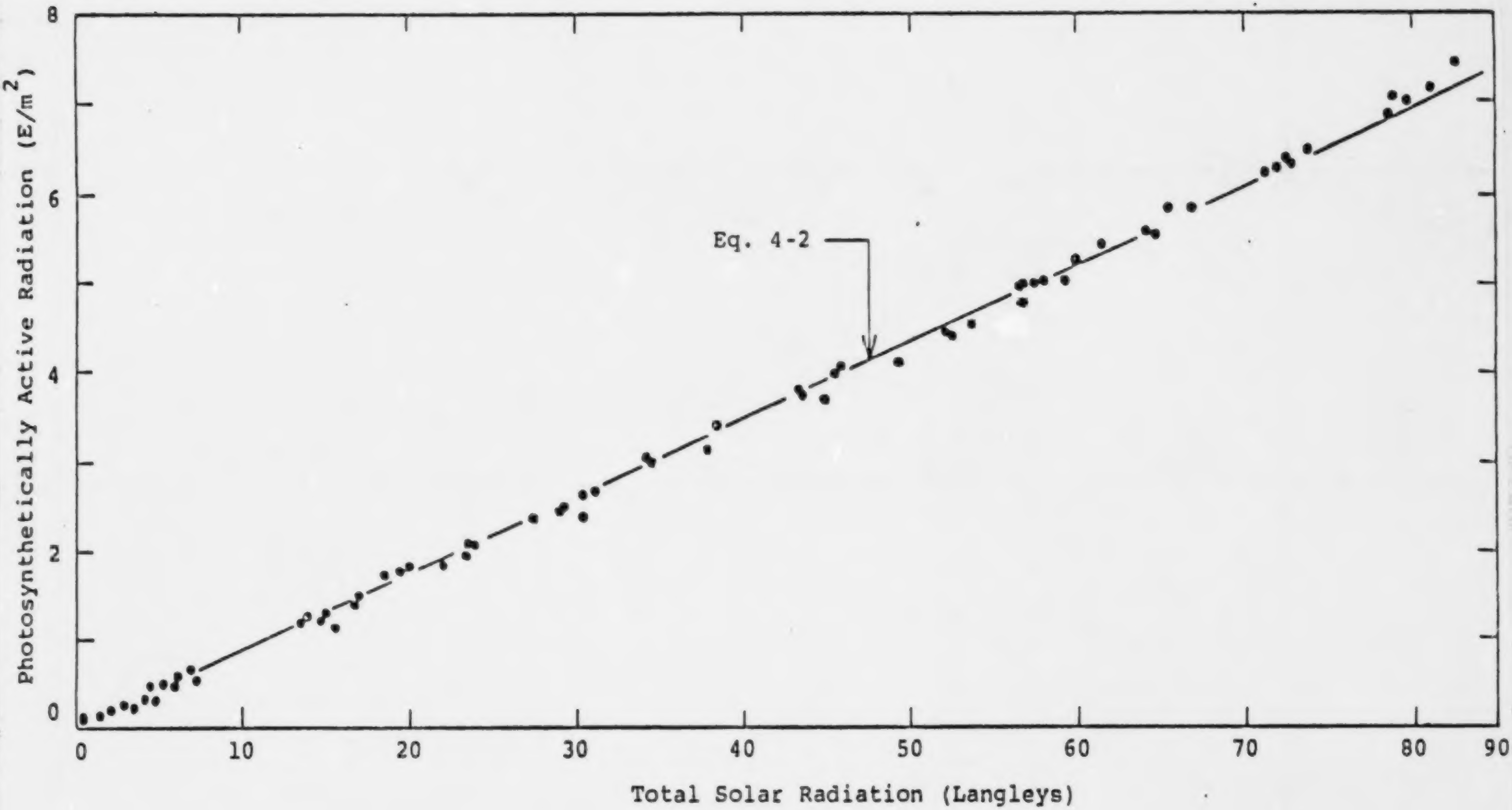

Fig. 4.3. Comparison of measured total solar radiation with measured photosynthetically active radiation from sunny and cloudy days. Measurements are hourly totals taken on 6/28/78, 7/11/78, 7/22/78, 7/23/78, and 9/1/78.

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SECTION 5

APPLICATION OF A GRAPHICAL PROCEDURE FOR STREAM PRODUCTIVITY ANALYSIS

A graphical procedure for stream productivity analysis was initiated to obtain quickly some preliminary results on respiration rates and photosynthetic rates in the MERS experimental streams. The information obtained in this way provides a first look at primary biological productivity in the channels and its dependence on light and temperature. Respiration rates have been assumed as constant. Surface oxygen exchange and longitudinal dispersion have been ignored. These approximations were necessary to keep the computations simple.

Equation 1-1 excluding the longitudinal dispersion and surface exchange term is

$$\frac{\partial C}{\partial t} = -U \frac{\partial C}{\partial x} + P - R \qquad (5\text{-}1)$$

If D.O. concentrations, $C(x_1, t)$ and $C(x_2, t)$ at two locations, x_1 and x_2, have been measured repeatedly over a period of time, the rate of photosynthesis can be determined from the difference in the measured concentrations lagged by the travel time:

$$P - R = \frac{C(x_2, t) - C\left(x_1, t - \dfrac{x_2 - x_1}{U}\right)}{(x_2 - x_1)/U} \qquad (5\text{-}2)$$

An example of measured diel D.O. curves, the upstream curve shifted in time by travel time, is given in Fig. 5.1. The apparent differences in D.O. at a given time reflect the value of P-R. If a value of the respiration, R, is available from an independent measurement, e.g. at predawn, the photosynthetic rate, P, can be calculated as shown in Table 5.1. Hourly rates of P-R and of R are listed in separate columns. Before sunrise and after sunset, photosynthesis is zero. Application of Eq. 5-2 will therefore give respiration rates. Frequently, predawn respiration rates were found to be less than post-sunset respiration rates.

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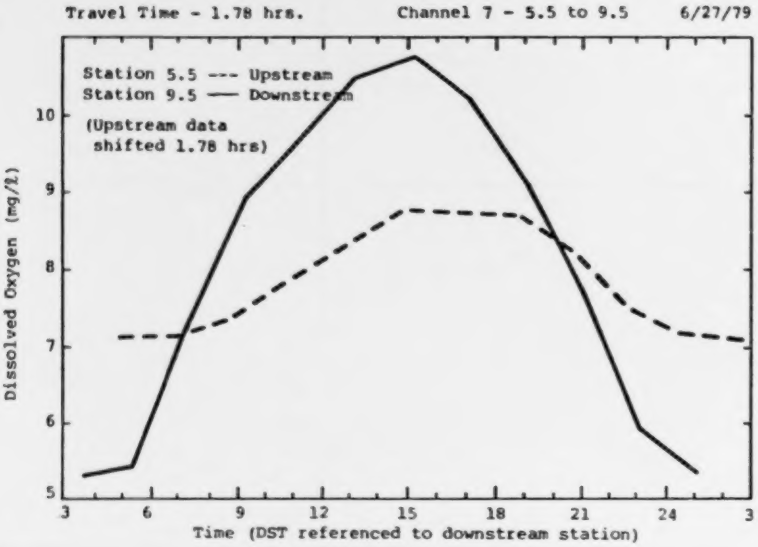

Fig. 5.1. Sample diel dissolved oxygen curves for the MERS experimental channels. The upstream D.O. curve is shifted by the travel time of the stream reach.

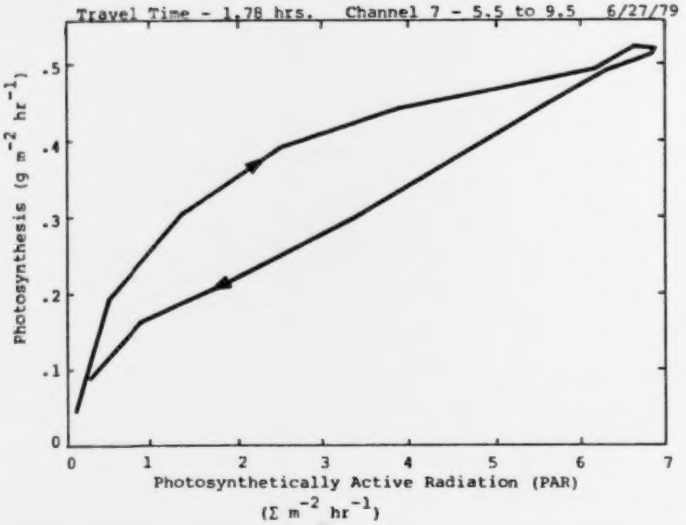

Fig. 5.2. Total community photosynthesis estimated by the graphical procedure versus measured PAR for the sample D.O. curves given in Fig. 5.1.

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TABLE 5.1. HOURLY RESPIRATION AND PHOTOSYNTHETIC RATES FROM THE SAMPLE DISSOLVED OXYGEN CURVES GIVEN IN FIG. 5.1

Location of Reach: from 5.5 to 9.5 Channel 7 Date: 6/27/79

Residence Time: 1.78 hrs.

Time at Lower Station	R	P-R	P	P	PAR	PAR adj. for travel time
	$g\ m^{-3}hr^{-1}$	$g\ m^{-3}hr^{-1}$	$g\ m^{-3}hr^{-1}$	$g\ m^{-2}hr^{-1}$	$E\ m^{-2}hr^{-1}$	$E\ m^{-2}hr^{-1}$
0000						
0100						
0200						
0300						
0400						
0500	.76	-.96				
0600	.76	-.60	.16	.04	.17	.10
0700	.76	-.08	.68	.19	.80	.52
0800	.76	.33	1.09	.30	1.83	1.38
0900	.76	.67	1.43	.39	3.13	2.56
1000	.76	.86	1.62	.44	4.56	3.93
1100	.76	.94	1.70	.47	5.76	5.23
1200	.76	1.04	1.80	.49	6.52	6.19
1300	.76	1.14	1.90	.52	6.83	6.69
1400	.76	1.13	1.89	.52	7.03	6.94
1500	.76	1.10	1.86	.51	6.81	6.91
1600	.76	1.01	1.77	.49	6.10	6.41
1700	.76	.84	1.60	.44	5.13	5.56
1800	.76	.58	1.34	.37	4.04	4.52
1900	.76	.29	1.05	.29	2.83	3.36
2000	.76	.06	.82	.22	1.48	2.07
2100	.76	-.19	.57	.16	.47	.91
2200	.76	-.47	.29	.08	.05	.23
2300	.76	-.77				
2400	.76	-.78				
		-.72				

Flow = 213 gpm

$\Sigma P = 5.92\ g\ m^{-2}day^{-1}$

$\Sigma R = 5.00\ g\ m^{-2}day^{-1}$

$\Sigma PAR = 63.5\ E\ m^{-2}day^{-1}$

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For these cases a "representative" post-sunset respiration rate was chosen. This choice is appropriate if surface exchange is the reason for the difference in respiration rates. Using the night value of R, values of P (in g m^{-3} hr^{-1}) were calculated throughout the day. Finally, R and P values were defined in terms of surface area (g m^{-2} hr^{-1}) by multiplying the previous values (g m^{-3} hr^{-1}) by the average depth of the channel section (m).

Hourly rates of photosynthesis (P) depend on light availability. P has therefore been plotted against photosynthetically active radiation (PAR) in Fig. 5.2 for the sample diel D.O. curves given in Fig. 5.1. The hourly PAR values measured by the quantum sensor are also shown in Table 5.1. PAR is that portion of solar radiation which plants can utilize in the photosynthetic process (400 - 700 nm). In the column to the right of the hourly PAR values are the weighted-average PAR values, based on the residence time of the parcel of moving water. This weighted average (based on a travel time of 1.78 hours) is calculated for a given hour as follows: 78 per cent of the previous hour's PAR is added to the given hour's PAR, and the result is divided by the hydraulic residence time (1.78 hours) to give the weighted average.

The above procedure was repeated for each set of diel D.O. measurements taken in the MERS experimental channels. The total daily values of P and R are compared with those determined from the numerical data analysis (DORM) in Section 8. The graphical procedure and the results for the MERS experimental channels are described in more detail by Mattke and Stefan (1980).

SECTION 6

DEVELOPMENT OF A NUMERICAL DISSOLVED OXYGEN ROUTING MODEL FOR STREAM PRODUCTIVITY ANALYSIS (DORM)

GENERAL DESCRIPTION OF MODEL

In this section a computer model titled the *Dissolved Oxygen Routing Model (DORM)* is developed which determines total community photosynthesis and respiration through iterative routing of (two station) diel dissolved oxygen measurements. The focus of the model is an unsteady finite difference simulation of the D.O. transport equation. The simplifying assumptions of the graphical procedure have been removed.

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(D_L \frac{\partial C}{\partial x}\right) + K_2\left(C_s - C\right) + P - R \qquad (6\text{-}1)$$

where C = D.O. concentration (g/m^3),
U = cross-sectional mean flow velocity (m/sec),
D_L = longitudinal dispersion coefficient (m^2/sec),
K_2 = surface exchange coefficient (sec^{-1}) = K_s/h
C_s = saturation D.O. concentration (g/m^3),
P = total community photosynthetic rate (g m^{-2} sec^{-1}),
R = total community respiratory rate (g m^{-2} sec^{-1}),
h = mean depth (m),
t = time (sec), and
x = distance along stream reach (m).

Flow rate and cross-sectional area are input to the model and are used to determine U . C_s is computed from water temperature (Rich, 1973), which is also input to the model.

Longitudinal dispersion is the spreading of material along the stream axis. It occurs in streams because the flow field is non-uniform, e.g. water moves faster in the center of the stream than along the edge. The longitudinal dispersion coefficient D_L is a bulk coefficient used in transport models. DORM uses the following equation for longitudinal dispersion coefficient.

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$$D_L = \frac{D^* Q}{\bar{b}} \qquad (6\text{-}2)$$

where Q = channel flow rate (m^3/sec),

$\bar{b}$ = average width of the channel reach, and

D^* = a dimensionless longitudinal dispersion coefficient which is constant for the channel reach.

Stefan et al (1980) found that $D^* = 7.47$ gave the best approximation of longitudinal dispersion in the MERS field channels.

Surface exchange coefficient is predicted with an equation developed by Gulliver and Stefan (1981b)

$$K_2 = 4A_1 \chi \; u^* \Big/ \left[h \, \ell n \left(\frac{\chi+1}{\chi-1} \right) \right] \qquad (6\text{-}3)$$

where $$\chi = \left[1 + \frac{R_D + A_7 \, (W \cos \alpha)^5}{4 \, A_1 \, Re_s^+} \right]^{\frac{1}{2}}$$

$Re_s^+ = \frac{u^* h}{\nu} \left(1 + A_5 \right)$, $u^* = (g \; h \; S)^{\frac{1}{2}}$ (m/sec),

S = water surface slope,

g = acceleration of gravity (m/sec^2),

$R_D = D_m / \nu$,

D_m = molecular diffusivity of oxygen in water (m^2/sec) ,

ν = kinematic viscosity of water (m^2/sec),

W = wind velocity (m/sec) ,

$A_1 = 5.44 \times 10^{-4}$,

A_5 = a constant representing the contribution of secondary currents to D.O. surface exchange,

A_7 = a constant related to the influence of wind on D.O. surface exchange, and

α = angle between wind direction and stream axis.

The constants, A_5 and A_7, are specific to each stream reach. Measurements of K_2 (Gulliver, 1980; Gulliver and Stefan, 1981b) indicated that for

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the MERS channel reaches studied $A_5 = 0.46$ and $A_7 = 3.8 \times 10^{-5}$ (m/sec)$^{-5}$ with wind velocity measured at 1.5 m above the water surface.

The effect of temperature on respiratory rate is included by the often used empirical relationship

$$R = R_{20}\ \theta^{T-20} \qquad (6\text{-}4)$$

where R_{20} = respiratory rate at 20°C ,
T = water temperature (°C) , and
θ = a constant.

Changes in R_{20} over time can be interpreted as a change in plant biomass. A relationship such as Eq. 6-4 is necessary to incorporate short-term variations in respiration due to diel variations in temperature. Plant biomass is assumed to be constant over the day.

At low D.O. concentrations respiratory rate is limited by D.O. For simplicity, the dependence of R on D.O. concentration is included by the Michaelis-Menten relationship because it is the most often used for limiting nutrients. Then Eq. 6-4 becomes

$$R = R_{20}\ \theta^{T-20}\ \frac{C}{C+C_{KM}} \qquad (6\text{-}5)$$

where C_{KM} is the half saturation coefficient. θ and C_{KM} are external inputs to DORM, although with low D.O. measurements successive runs of DORM may be used to determine C_{KM}. R_{20} in Eq. 6-5 is the respiratory constant at high D.O.; it is estimated in DORM. DORM assumes that for a given stream reach R_{20} is constant over the study period, which is normally 24 or 48 hours. Thus, R_{20} can be seen as an indicator respiration for a given level of plant biomass.

Diel curve analysis in DORM is performed in the following manner:

a. DORM begins with a reach of specified length, distance increment, and time increment. The stream reach is then divided into a number of segments. Each segment is assumed to have a constant surface width, cross-sectional area, and water surface slope and many consist of one or more distance increments.

b. An algebraic equation of an order specified by the user is fit through the upstream D.O. measurements to give the best possible continuous simulation of inflowing D.O. concentration. The equation will interpolate between D.O. measurements.

c. An initial estimate of R_{20} is found by successively routing predawn D.O. with Eq. 6-1 through the channel and adjusting R_{20} until the mean error between predicted and measured D.O. concentration at the downstream location is small.

d. Values of P corresponding to each downstream D.O. measurement during daylight hours are found by settling R_{20} as previously determined, predicting D.O. concentration during daylight hours from Eq. 6-1, and readjusting each value of P with the residual between each predicted and measured D.O. concentration. This process is repeated until all residuals are small (less than .001 g m^{-2} hr^{-1}).

e. Using the P values determined in d above, D.O. concentration at the downstream location is predicted for the full 24 hour period. R_{20} is adjusted by comparing downstream predicted and measured D.O. concentrations for both predawn and post-sunset periods. The full 24 hour predictions are repeated until the adjustment in R_{20} is small (less than .001 g m^{-2} hr^{-1}). If any adjustment of R_{20} is required at this step, the program returns to the analysis mentioned in (d) above. Otherwise the routing is complete and the results are output.

Two advantages to DORM are that surface exchange rate can be varied with distance, and that longitudinal dispersion may be modelled. The results of the model may be used to test many of the assumptions made in community productivity measurements, e.g. the dependence of R on temperature and D.O. concentration or the importance of surface exchange. DORM may also be used to estimate P and R for a number of consecutive days where R_{20} is assumed to be the same for all days of the study period. A general flow chart for DORM is given in Fig. 6.1. A program listing for DORM is given in Appendix A. Comment statements in the program listing will provide a more detailed description of the program operation.

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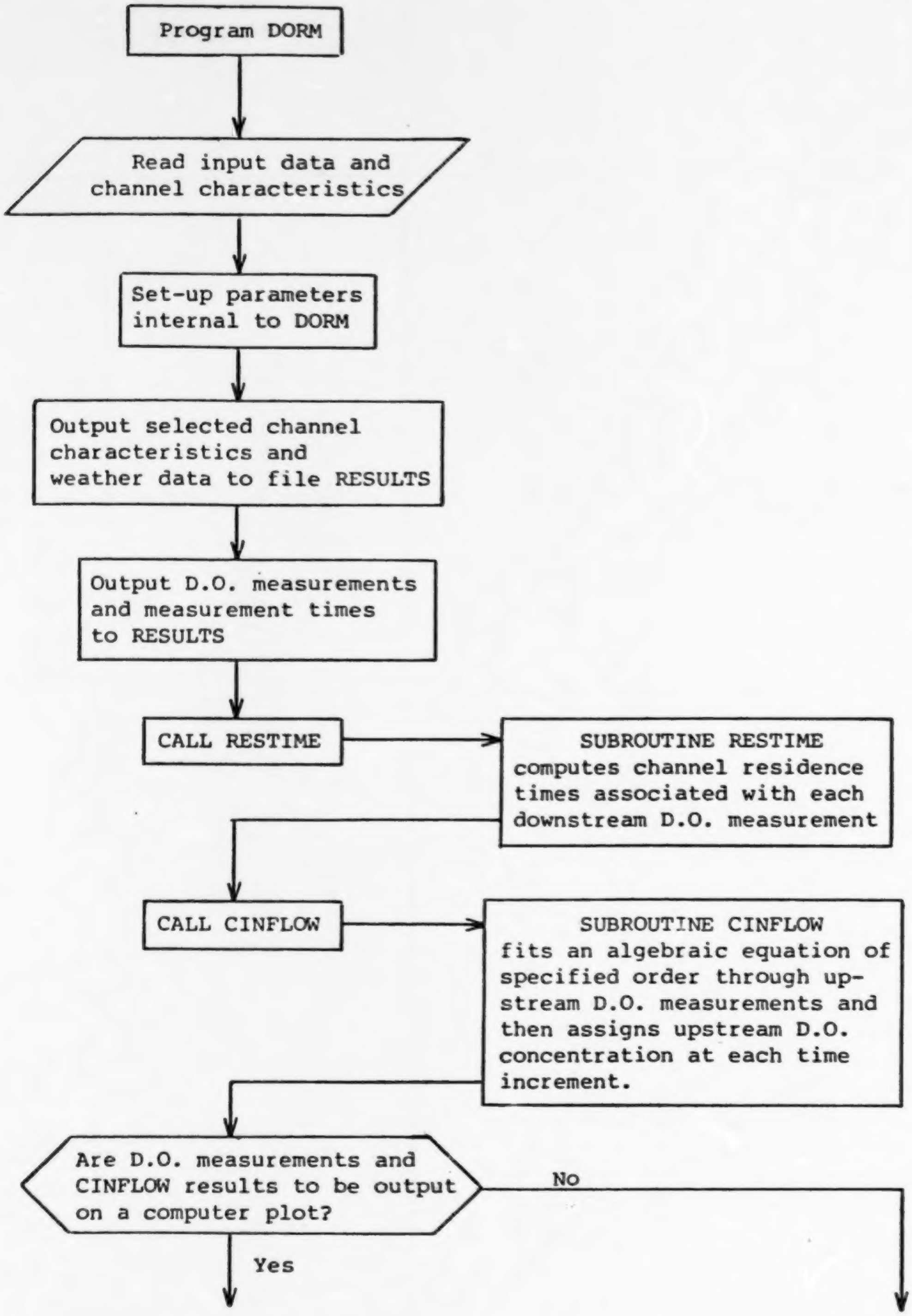
Program DORM
Read input data and channel characteristics
Set-up parameters internal to DORM
Output selected channel characteristics and weather data to file RESULTS
Output D.O. measurements and measurement times to RESULTS
CALL RESTIME
SUBROUTINE RESTIME computes channel residence times associated with each downstream D.O. measurement
CALL CINFLOW
SUBROUTINE CINFLOW fits an algebraic equation of specified order through upstream D.O. measurements and then assigns upstream D.O. concentration at each time increment.
Are D.O. measurements and CINFLOW results to be output on a computer plot?
No
Yes

Fig. 6.1. General flow chart for the dissolved oxygen routing model.

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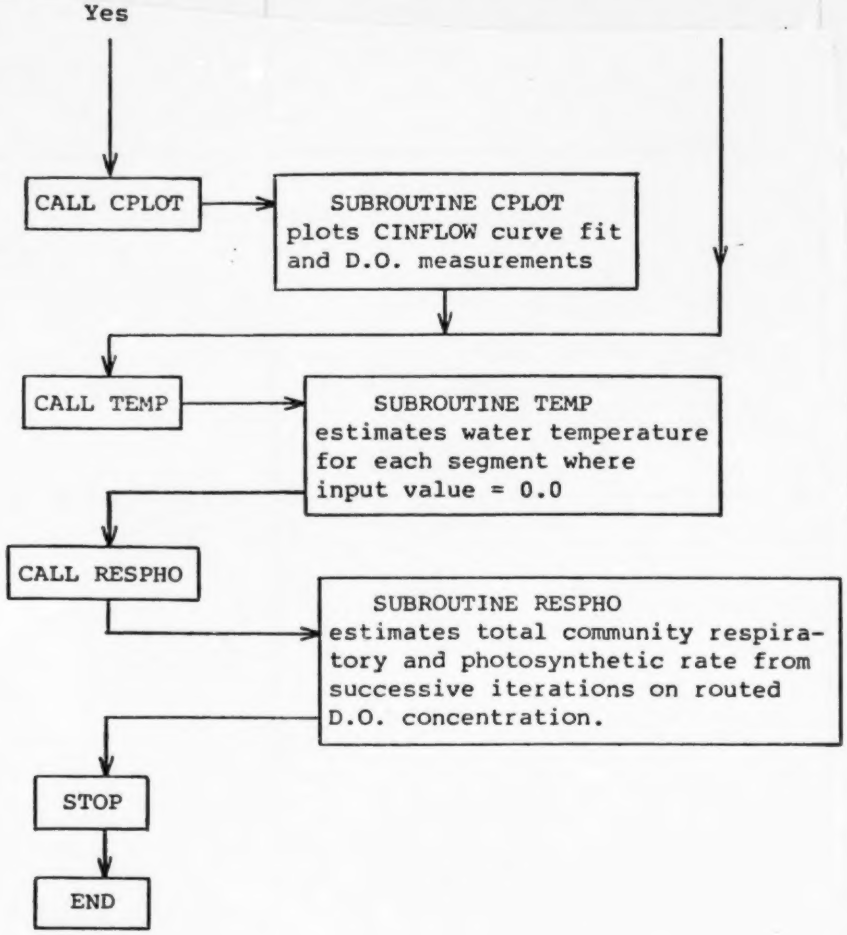
Yes
CALL CPLOT
SUBROUTINE CPLOT plots CINFLOW curve fit and D.O. measurements
CALL TEMP
SUBROUTINE TEMP estimates water temperature for each segment where input value = 0.0
CALL RESPHO
SUBROUTINE RESPHO estimates total community respiratory and photosynthetic rate from successive iterations on routed D.O. concentration.
STOP
END

Fig. 6.1 (Cont'd).

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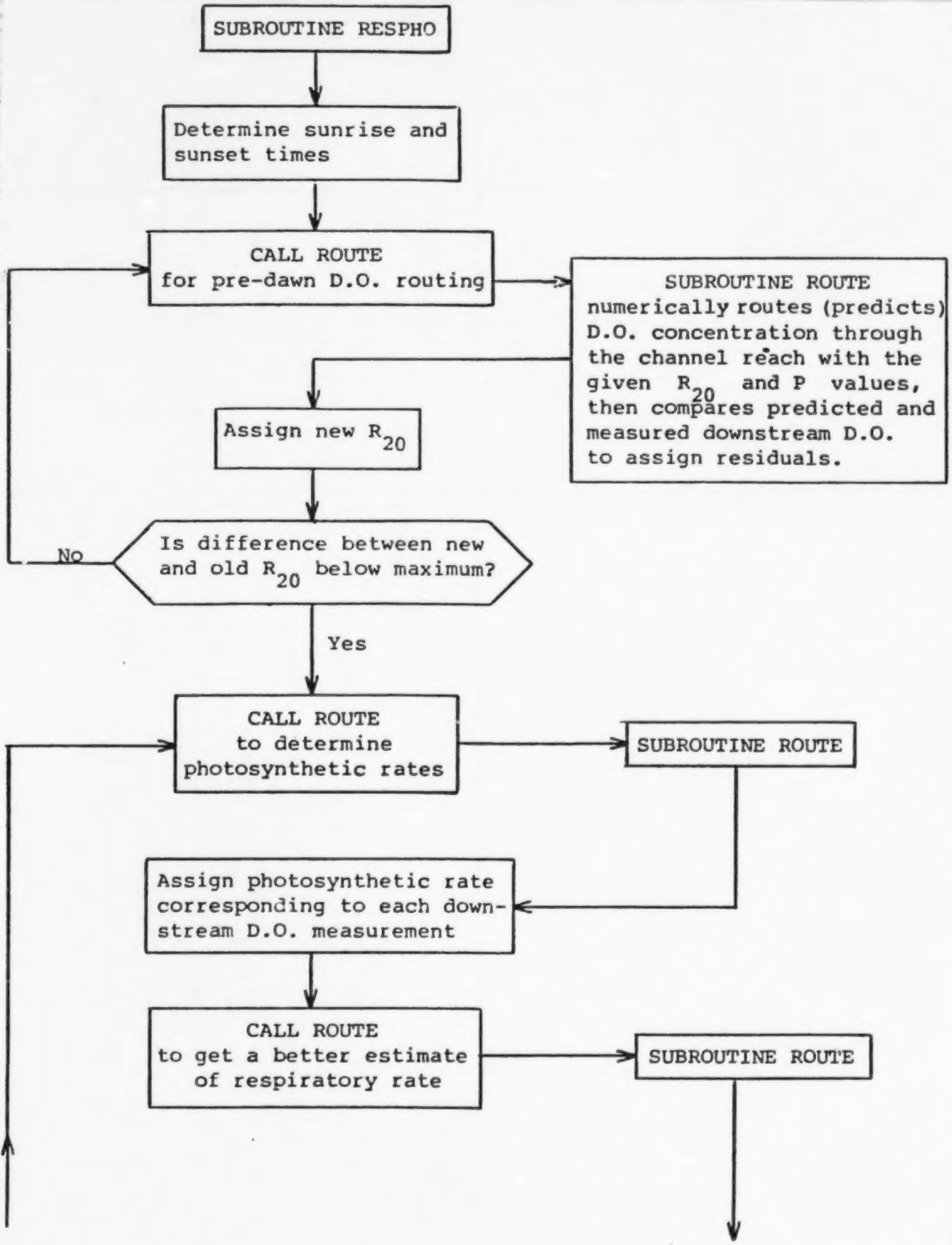
SUBROUTINE RESPHO
Determine sunrise and sunset times
CALL ROUTE for pre-dawn D.O. routing
SUBROUTINE ROUTE numerically routes (predicts) D.O. concentration through the channel reach with the given R_{20} and P values, then compares predicted and measured downstream D.O. to assign residuals.
Assign new R_{20}
Is difference between new and old R_{20} below maximum?
No
Yes
CALL ROUTE to determine photosynthetic rates
SUBROUTINE ROUTE
Assign photosynthetic rate corresponding to each downstream D.O. measurement
CALL ROUTE to get a better estimate of respiratory rate
SUBROUTINE ROUTE

Fig. 6.1 (Cont'd).

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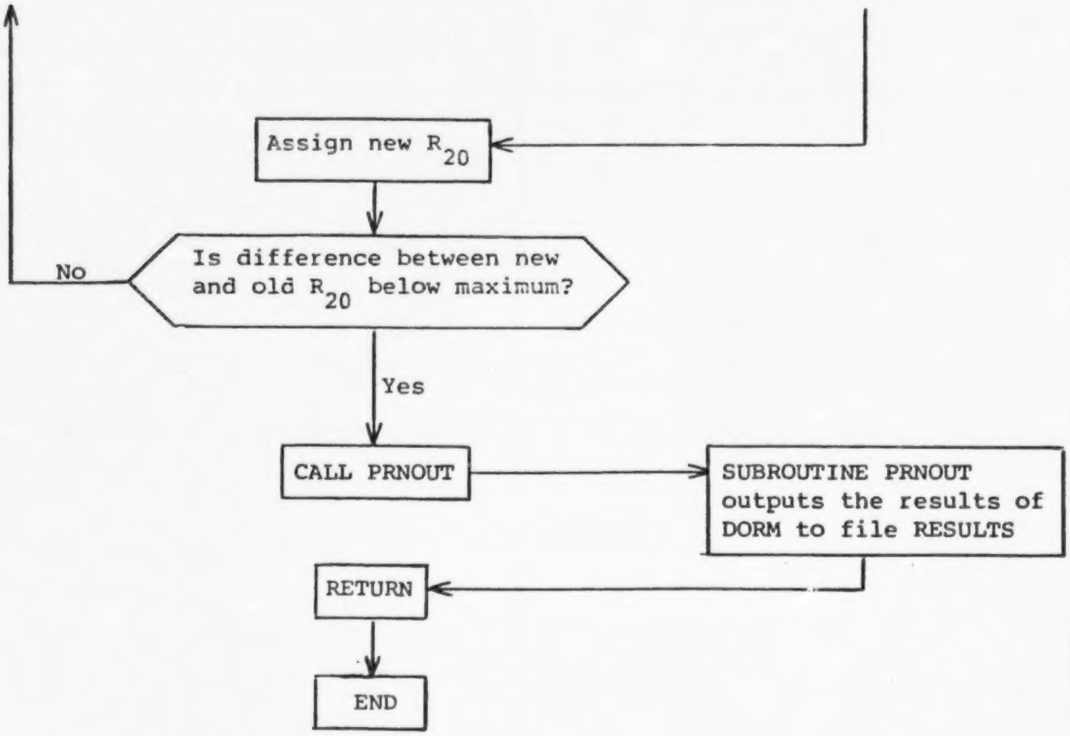
Assign new R_{20}
Is difference between new and old R_{20} below maximum?
No
Yes
CALL PRNOUT
SUBROUTINE PRNOUT outputs the results of DORM to file RESULTS
RETURN
END

Fig. 6.1 (Cont'd).

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Required input data for DORM are

- D.O. measurements for both upstream and downstream stations and time of measurement for each D.O. measurement.
- For each segment: cross-sectional area, surface width, segment length, water surface slope, and initial D.O. concentration.
- Water temperature for each channel segment, wind velocity, and wind direction at a specified time interval.
- Average flow rate and air pressure for the simulation time period.
- Computational parameters described in Appendix B.

The User's Instructions for DORM in Appendix B gives a more detailed description of all required input data. The most important input parameters for accurate productivity analysis are measured D.O. concentrations, flow rate, cross-sectional area, water surface slope, and water temperature.

FORMULATION OF FINITE DIFFERENCE EQUATIONS

Each time diel dissolved oxygen measurements are routed through the channel reach in DORM, Eq. 6-1 is solved by the finite difference method described herein. The solution method uses implicit hybrid finite differences for unsteady one-dimensional prediction of D.O. concentration.

The finite difference equation for Eq. 6-1 will be formulated about $i, j+\frac{1}{2}$ in the control volume given in Fig. 6-2a. The distance and time steps are the i and j locations on the x- and t-axes, respectively.

For the control volume in Fig. 6.2a, Eq. 6-1 may be rewritten as

$$\frac{C_{i,j+1} - C_{i,j}}{\Delta t} = \text{Flux}_{i-\frac{1}{2},j+\frac{1}{2}} - \text{Flux}_{i+\frac{1}{2},j+\frac{1}{2}} + \frac{K_s}{h}\left(C_s - C_{i,j+\frac{1}{2}}\right) + P-R \qquad (6\text{-}6)$$

For the flux terms in Eq. 6-6, two specifications are necessary. With respect to the time axis the terms may be:

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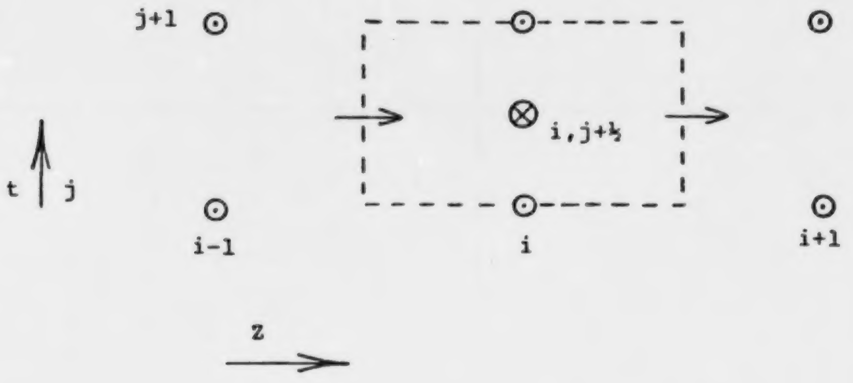

Fig. 6.2a. Control volume for formulation of unsteady, one-dimensional finite difference equation.

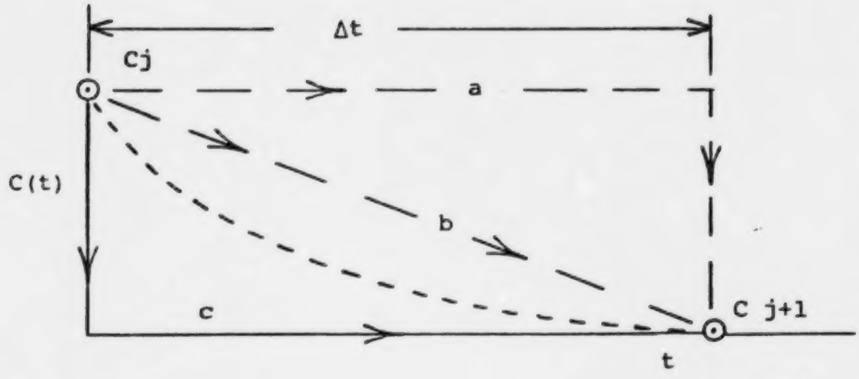

Fig. 6.2b. Assumed concentration versus time for one time step at a given distance location i. a-explicit; b-Crank-Nicolson implicit; c-fully implicit. Dashed line indicates possible path of exact C(t).

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a. **Explicit**:

$$\text{Flux}_{i-\frac{1}{2},\ j+\frac{1}{2}} \rightarrow \text{Flux}_{i+\frac{1}{2},\ j} \tag{6-7a}$$

$$\text{Flux}_{i+\frac{1}{2},\ j+\frac{1}{2}} \rightarrow \text{Flux}_{i+\frac{1}{2},\ j} \tag{6-7b}$$

b. **Crank-Nicolsen implicit**:

$$\text{Flux}_{i-\frac{1}{2},\ j+\frac{1}{2}} \quad \frac{\text{Flux}_{i-\frac{1}{2},j} + \text{Flux}_{i-\frac{1}{2},\ j+1}}{2} \tag{6-8a}$$

$$\text{Flux}_{i+\frac{1}{2},\ j+\frac{1}{2}} \quad \frac{\text{Flux}_{i+\frac{1}{2},j} + \text{Flux}_{i+\frac{1}{2},\ j+1}}{2} \tag{6-8b}$$

c. **Fully implicit**:

$$\text{Flux}_{i-\frac{1}{2},\ j+\frac{1}{2}} \quad \text{Flux}_{i-\frac{1}{2},\ j+1} \tag{6-9a}$$

$$\text{Flux}_{i+\frac{1}{2},\ j+\frac{1}{2}} \quad \text{Flux}_{i+\frac{1}{2},\ j+1} \tag{6-9b}$$

The implications of the three specifications are illustrated in Fig. 6.2b, where concentration versus time is given for each specification of a given value of i.

For the x-axis a number of specifications are possible for the flux terms.

a. Upstream differences (Courant et al, 1952; Runchal and Wolshtein, 1979) are applicable when convective transport is dominant over diffusion or dispersion. Then the flux terms become

$$\text{Flux}_{i-\frac{1}{2}} = F_{i-\frac{1}{2}} = \frac{Q}{A\Delta x}\left(C_{i-1} + \frac{C_{i-1} - C_i}{Pe_{i-\frac{1}{2}}}\right) \tag{6-10a}$$

$$F_{i+\frac{1}{2}} = \frac{Q}{A\Delta x}\left(C_i + \frac{C_i - C_{i+1}}{Pe_{i+\frac{1}{2}}}\right) \tag{6-10b}$$

where $Pe = Q\Delta x/(AD_L)$ is the grid Peclet number.

b. **Central differences** are applicable when diffusive transport dominates over convection. Then the flux terms are written as

$$F_{i-\frac{1}{2}} = \frac{Q}{A\Delta x}\left(\frac{C_{i-1} + C_i}{2} + \frac{C_{i-1} - C_i}{Pe_{i-\frac{1}{2}}}\right) \tag{6-11a}$$

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$$F_{i+\frac{1}{2}} = \frac{Q}{A\Delta x}\left(\frac{C_i + C_{i+1}}{2} + \frac{C_i - C_{i+1}}{Pe_{i+\frac{1}{2}}}\right) \qquad (6\text{-}11b)$$

c. A number of Hybrid difference schemes have been proposed (Saitoh, 1977; Spalding, 1972). One which is often used is the analytical one-dimensional steady state solution for the flux between two points of known concentration (Chien, 1977; Fiaderiro and Veronis, 1977). With this formulation the flux terms become

$$F_{i-\frac{1}{2}} = \frac{Q}{A\Delta x}\left(C_{i-1} + \frac{C_{i-1} - C_i}{\exp(Pe)_{i-\frac{1}{2}} - 1}\right) \qquad (6\text{-}12a)$$

$$F_{i+\frac{1}{2}} = \frac{Q}{A\Delta x}\left(C_i + \frac{C_i - C_{i+1}}{\exp(Pe)_{i+\frac{1}{2}} - 1}\right) \qquad (6\text{-}12b)$$

herein called the exponential difference scheme. The exponential term in Eq. 6-12 is expensive to compute at large Pe. For this reason the following power law approximation by Patarkar and Baliga (1978) is used in DORM:

$$\frac{1}{\exp(Pe) - 1} = \text{AMAX}\left[\ 0,\ \left(1 - 0.1\,|Pe|\right)^5 / Pe\ \right] \qquad (6\text{-}13)$$

where AMAX [ ] signifies the larger of the two terms in brackets.

Spalding (1972) has shown that where a large range of Peclet numbers is to be applied, a hybrid difference formulation is necessary. The upstream difference scheme gives a large error at low Pe (< 2) and the central difference scheme gives a large error at a large Pe (> 2).

For use in DORM, Eq. 6-6 has been formulated in exponential differences using Eq. 6-13. A coefficient ε is used to specify whether the scheme is fully implicit, C-N implicit, or explicit. Then Eq. 6-6 is written as

$$b\,C_{i,\,j+1} = a\,C_{i-1,\,j+1} + c\,C_{i+1,\,j+1} + d \qquad (6\text{-}14)$$

where $a = F_{c_{i-1}}\,\varepsilon\left\{1 + \text{AMAX}\left[0,\ \frac{(1 - 0.1\,Pe_{i-1})^5}{Pe_{i-1}}\right]\right\}$

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$$c = \varepsilon F_{c_i} \text{ AMAX}\left[0, \frac{(1 - 0.1\, Pe_i)^5}{Pe_i}\right]$$

$$b = 1 + a + c + \frac{\varepsilon \Delta t\, K_s}{h}$$

$$d = C_{i,j} + \frac{1-\varepsilon}{\varepsilon}\left[a\, C_{i-1,j} - \left(a + c + \frac{\varepsilon \Delta t\, K_s}{h}\right) C_{i,j} + c\, C_{i+1,\,j}\right] + \frac{\Delta t}{h}\left(P - R + K_s\, C_s\right)$$

$F_{c_i} = \frac{Q\Delta t}{A_i \Delta x}$ = a grid flux Courant number

$Pe_i = \frac{Q\Delta x}{A_i\, D_{L_i}}$, and

$\varepsilon = 1$ gives fully implicit,

$\varepsilon = 1/2$ gives C-N implicit, and

$\varepsilon = 0$ gives explicit finite differences.

ε may be any value between 0 and 1. The distance increments are formulated such that $Pe_{i-\frac{1}{2}} = Pe_{i-1}$.

ANALYSIS OF NUMERICAL ACCURACY

A Crank-Nicolson implicit scheme ($\varepsilon = 0.5$) generally gives a more accurate simulation of Eq. 6-1 except when

$$F_c\left(\varepsilon + \frac{1}{\exp(Pe) - 1}\right) > 1 \qquad (6\text{-}15)$$

because oscillations in the computed solution are possible with C-N differences (d in Eq. 6-14 becomes negative). Thus oscillation is possible if

$$F_c > \frac{1}{\varepsilon + \frac{1}{\exp(Pe) - 1}} \qquad (6\text{-}16)$$

Equation 6-16 with $\varepsilon = 0.5$ will give the minimum value of F_c at which oscillation can occur for C-N differences. Calculations on Eq. 6-16 give:

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Pe	10	3	2	1	0.5	0.3	0.1	0.01
Minimum value of F_c for possible oscillation	2	1.81	1.52	0.92	0.49	.3	.1	.01

Thus, it is only at large values of Pe that C-N differences are preferable over fully implicit differences.

In Eqs. 6-15 and 6-16 the grid Peclet number, Pe , determines to what extent dispersion is included in the solution. Thus, Pe may be seen as a comparison of numerical and real dispersion in the computer solution. At small Pe, real dispersion is dominant. At large Pe, numerical diffusion is dominant. To model dispersion, we should have $Pe \le 1$.

Banks (1974) in studying a one-dimensional unsteady mixed cell model has shown that at an infinite number of cells the model is equivalent to the transport model of Eq. 6-1 where the term $1/2\ U\Delta x$ replaces the dispersion coefficient. If we define a numerical diffusion coefficient,

$$D_{num} = U\Delta x/2 \tag{6-17}$$

then the grid Peclet number may be expressed as

$$Pe = 2D_{num}/D_L \tag{6-18}$$

Although D_{num} is only truly equivalent to a dispersion coefficient at an infinite number of cells, it gives a valid estimate of existing numerical diffusion with a finite number of cells.

Equation 6-17 explains why, with a large Pe, dispersion is excluded from consideration in the numerical solution. With a large Pe, dispersion is not being modelled since numerical diffusion is much larger than that specified by the value of D_L . Any dispersion apparent in the solution is due to numerical error, rather than true dispersion. If dispersion is an important consideration, then a small grid Peclet number must be used in the computation.

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SOLUTION METHOD

To solve for D.O. concentrations at all locations $i (1 < i < I)$ on the stream reach at time $t = j+1$, Eq. 6-14 is first rewritten as

$$C_{i,\, j+1} + W_i\, C_{i+1,\, j+1} = G_i \tag{6-19}$$

where at all locations except the boundaries:

$$W_i = \frac{-c}{b + a\, W_{i-1}} \tag{6-20}$$

and

$$G_i = \frac{a\, G_{i-1} + d_{i,j}}{b + a\, W_{i-1}} \tag{6-21}$$

At $i=1$, $C_{1,\, j+1}$ is known and

$$W_2 = -c/b, \quad G_2 = \frac{d_2 + a\, C_{1,\, j+1}}{b} \tag{6-22}$$

At the lower end of the stream reach $(i=I)$, a constant gradient of D.O. concentration is assumed, or

$$C_{I+1,\, j+1} = 2\, C_{I,\, j+1} - C_{I-1,\, j+1} \tag{6-23}$$

Then,

$$W_I = 0 \, , \tag{6-24a}$$

$$G_I = \frac{(a-c)\, G_{I-1} + d_{I,j}}{b - 2c + (a-c) W_{I-1}} \tag{6-24b}$$

and finally

$$C_{I,\, j+1} = G_I \tag{6-24c}$$

The longitudinal dissolved oxygen profile is then solved through back substitution from $i=I-1$ to $i=2$ with a rearranged form of Eq. 6-19:

$$C_{i,\, j+1} = G_i - W_i\, C_{i+1,\, j+1} \tag{6-25}$$

Equations 6-20 through 6-25 form a tridiagonal matrix.

CURVE-FITTING PROCEDURE FOR D.O. INPUT DATA

For the diel curve method of productivity analysis the upstream D.O. measurements are taken at given time intervals. A sample of some typical upstream D.O. measurements is given in Fig. 6.3. For most D.O. routing methods and specifically for DORM, a continuous input of upstream D.O. concentration is necessary. Therefore the gaps between the D.O. measurements must be filled by a curve-fitting procedure which interpolates between discrete data points.

The simplest curve-fitting procedure is to use a straight line to describe D.O. concentration between D.O. measurements. This will give sufficiently accurate results if upstream D.O. concentration does not have a large diel cycle or if measurements are taken at close intervals. A linear approximation is usually sufficient with two hour sampling intervals. There are occasions, however, when the linear approximation will exclude significant portions of the continuous curve for upstream D.O. concentration. For this reason the upstream D.O. concentration between D.O. measurements is approximated in DORM as

$$C = \sum_{i=0}^{i=N} a_i \, t^i \tag{6-26}$$

where a_i = coefficients determined from D.O. measurements,

t = time, and

N = the order of Eq. 6-26 which may be any integer.

Curves for $N = 1$, 3, and 5 are compared in Fig. 6.3. $N=1$ is the linear approximation. The curve-fitting procedure operates in the following manner:

> Consider $N=3$. A curve for D.O. concentration is to be approximated between measurement times t_1 and t_2. Four constants, a_0, a_1, a_2, and a_3 need to be determined in Eq. 6-26. Four D.O. measurements are therefore needed. C_0, C_1, C_2, and C_3 at measurement times t_0, t_1, t_2, and t_3 will be used. The four measurement times and the four D.O. measurements substituted in Eq. 6-26 give a 4x4 linear matrix which may be solved for all a_i values.

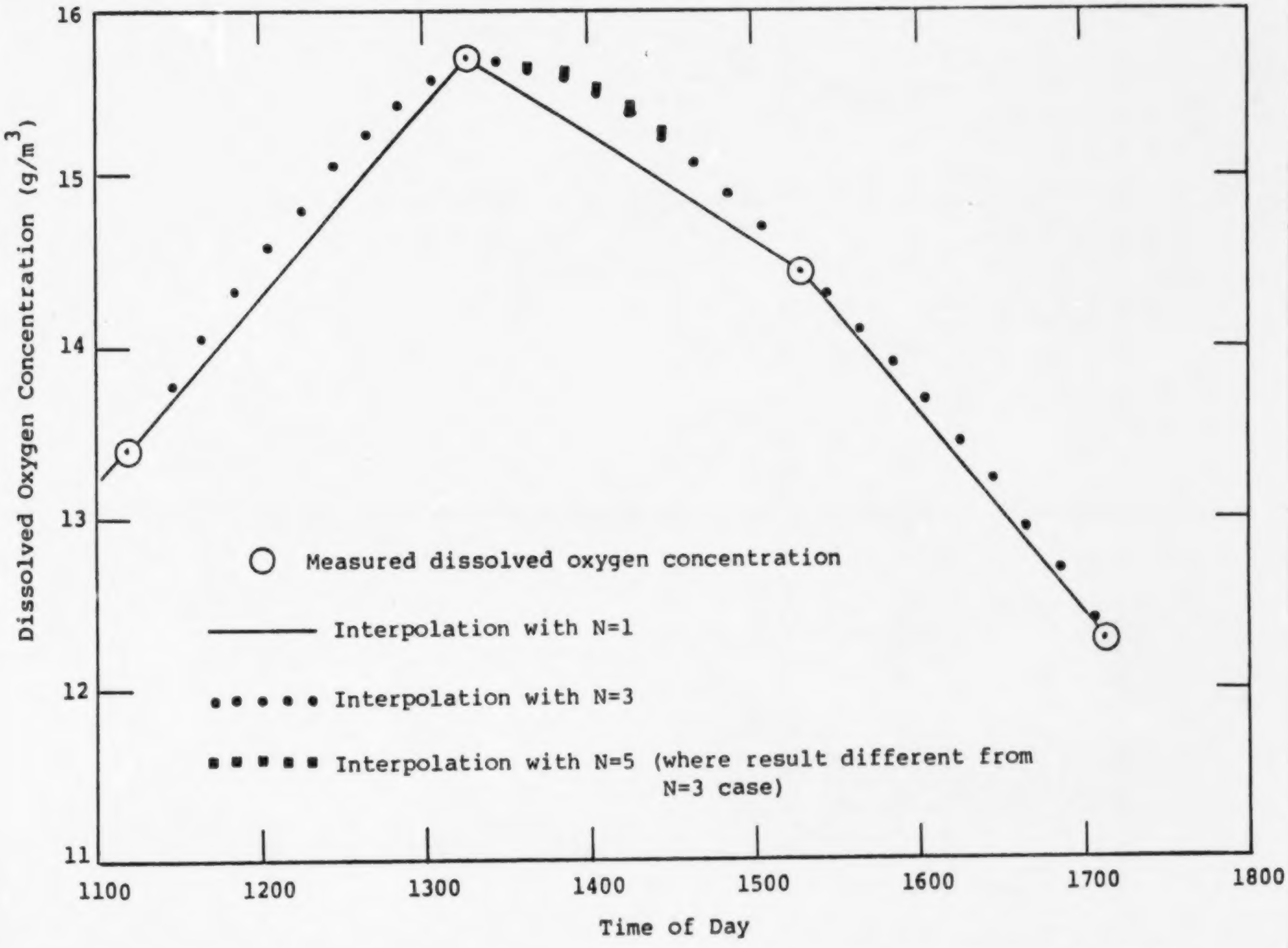

Fig. 6.3. Sample of continuous curve interpolation between upstream dissolved oxygen measurements with N=1, 3, and 5.

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$$C_0 = a_0 + a_1 t_0 + a_2 t_0^2 + a_3 t_0^3$$

$$C_1 = a_0 + a_1 t_1 + a_2 t_1^2 + a_2 t_1^3$$

$$C_2 = a_0 + a_1 t_2 + a_2 t_2^2 + a_3 t_2^3$$

$$C_3 = a_0 + a_1 t_3 + a_2 t_3^2 + a_3 t_3^3$$

The above precedure is repeated to determine a set of a_i values for each pair of measurement times. Thus, if there are 13 upstream D.O. measurements, there will be 12 sets of a_i values which are computed in DORM.

DETERMINATION OF TOTAL COMMUNITY RESPIRATORY RATE PARAMETERS

Concept

In order to apply DORM to diel curve analysis of stream productivity, two parameters incorporating the stream community's respiratory response to water temperature and dissolved oxygen concentration must be determined. The temperature coefficient, θ, for the respiratory response to water temperature was determined from predawn longitudinal surveys of D.O. concentration in channel 7 which were taken in the fall of 1978. The half-saturation coefficient C_{KM} in Eq. 6-5 was then determined from one set of diel D.O. measurements taken in a lower reach of channel 6, where D.O. concentration decreased to 2.8 g/m^3 during the night. Nutrient measurements in the channels (Taylor and Sheldon, 1980) indicated that nutrient concentrations in the water did not limit photosynthesis and respiration. The nutrient data are given in Appendix D.

Temperature Coefficient for Respiratory Rate

During a predawn longitudinal D.O. survey there is no photosynthetic production and there has not been any photosynthesis during several preceding hours. In addition, continuous D.O. measurements in the MERS field channels indicate that beginning about mid-August a quasi-steady state dissolved oxygen condition develops during the late night hours, and D.O. concentration at each location is constant with time. Therefore a single longitudinal D.O. survey may be used to characterize total community respiratory rate in a stream reach. Given the measured

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longitudinal D.O. gradients and D_L values of the MERS channels, the effect of longitudinal dispersion is negligible in the analysis of predawn D.O. surveys. Surface exchange of oxygen, however, must still be included in the analysis.

A predawn longitudinal D.O. survey consisted of up to 18 individual dissolved oxygen measurements made in rapid succession (within a 30 minute period) at the beginning and end of each riffle. In late summer and fall of 1978 seven longitudinal D.O. profiles were taken within 15 days to compare respiratory rates for a community biomass which had not changed greatly. After this period, three more profiles were taken at one week intervals. A heat wave occurred in early September and ended abruptly between two surveys which were spaced by one day. Thus, a suitable range in water temperature (17 to 23°C) was achieved over the period. Measured longitudinal D.O. profiles are given for each survey by Gulliver and Stefan (1981a). Figure 6.4 shows an example. The separate effects of riffles and pools can be seen, but are lumped into one curve in Fig. 6.4. The channel is divided into two sections: an unshaded section downstream and a shaded section in the upper half of the channel. Shade was provided by a man-made burlap canopy several feet above the channel. The purpose of the shade was to reduce macrophyte growth to facilitate biological observation and sampling by the MERS staff. This section of the channel was inadequate for primary productivity studies because the shading was not uniform throughout the day or along the channel and the average light incoming to the water surface could not be determined. Therefore, only the unshaded section was used for productivity analysis and discussion herein will focus on that part of the channel.

For the predawn D.O. profile, there is no photosynthetic production, longitudinal dispersion may be neglected, and steady state is assumed. Then Eq. 6-1 is simplified to:

$$U \frac{dC}{dx} = K_2(C_s - C) - R \qquad (6\text{-}27)$$

where U = cross section mean flow velocity,
x = distance downstream,
C = D.O. concentration,

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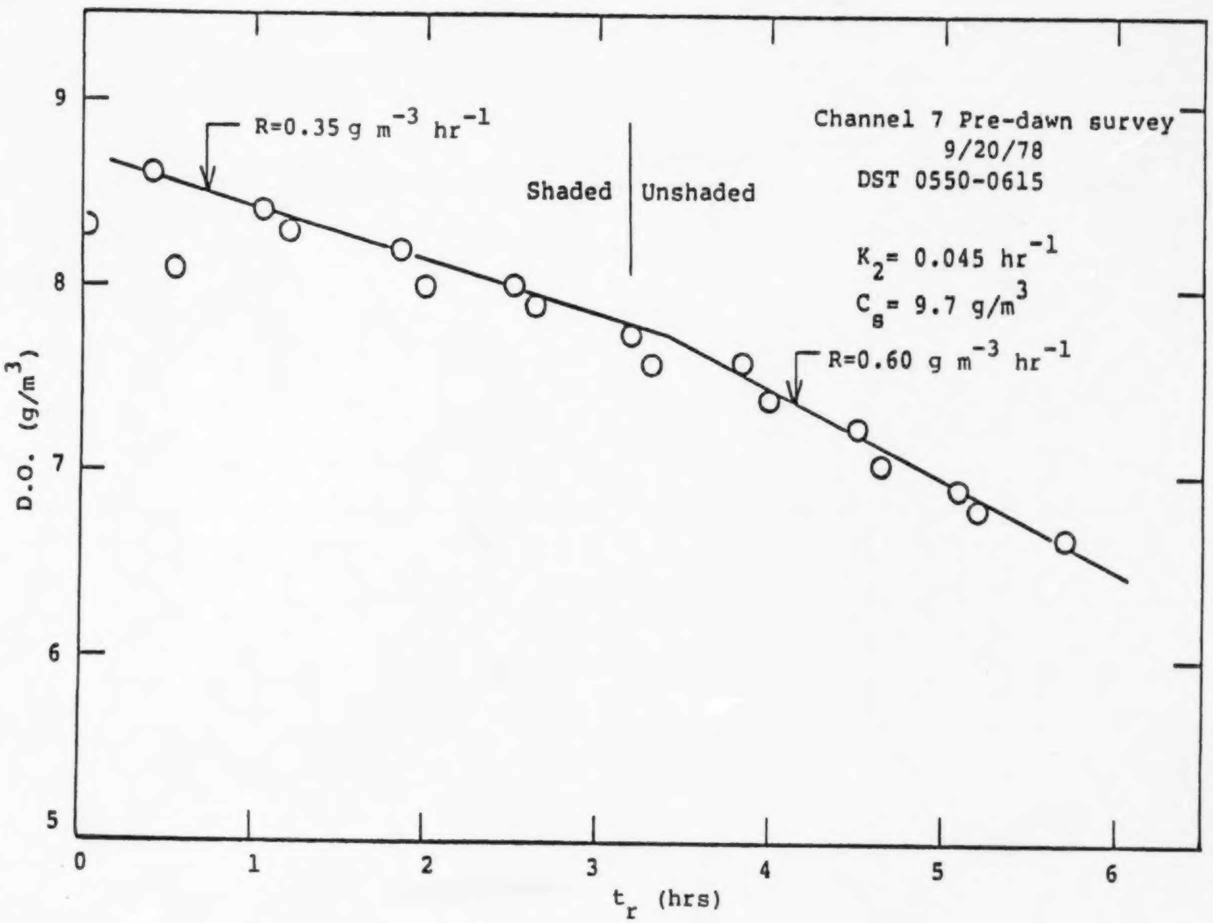

Fig. 6.4. Typical predawn longitudinal dissolved oxygen profile. Channel 7, 9/20/78.

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K_2 = surface exchange coefficient = K_s/h, and

C_s = saturation D.O. concentration.

If the channel location is specified by the travel time (or residence time) from the beginning of the channel to that location

$$t_r = x/U \qquad (6\text{-}28)$$

Equation 6-27 becomes

$$\frac{C}{t_r} = K_2(C_s - C) - R \qquad (6\text{-}29)$$

If $C = C_o$ and $t_r = t_{to}$ at the upstream end of the unshaded channel section, then Eq. 6-29 has the solution

$$C = (C_o + R/K_2 - C_s)e^{-K_2(t_r - t_{ro})} + C_s - R/K_2 \qquad (6\text{-}30)$$

C was plotted with respect to t_r for all longitudinal D.O. surveys as shown in Fig. 6.4. Also given is the curve fit of Eq. 6-30 to the data, which was used to determine R. The surface exchange coefficient, K_2, was computed from Eq. 6-3 with $A_5 = 0.46$ and $A_7 = 4.2\text{x}10^{-5}$ (m/sec)$^{-5}$. The curvature in these lines is very small because the D.O. deficit ($C_s - C$) does not change greatly over the unshaded reach. The application of Eq. 6-30 indicated that surface exchange reduced the longitudinal D.O. gradient by an average of 16 per cent.

The total community respiratory rates derived from the data are given in Table 6.1. Respiratory rates in the unshaded section were consistently higher than those in the shaded section. The difference of about 30 per cent reflects greater primary biological activity and plant biomass in the channel reach exposed to more light. A semi-log graph of respiratory rates versus water temperature given in Fig. 6.5 was used to determine θ for the unshaded channel reach.

Respiration rates also depend upon plant biomass. One must therefore be very cautious with this type of plot because it may also represent a gain or loss in plant biomass over time as well as the community response to water temperature. For this reason emphasis was placed on the data taken within a short time period. (The 8/30 predawn profile

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TABLE 6.1. TOTAL COMMUNITY RESPIRATORY RATES FROM PREDAWN LONGITUDINAL DISSOLVED OXYGEN PROFILES IN CHANNEL 7

		Shaded Section, Reach 3-10						Unshaded Section, Reach 11-19					
Date	Flow Rate	t_r	T	C_s	K_2	R/h	R	t_r	T	C_s	K_2	R/h	R
	gpm	hr	^oC	g/m^3	hr^{-1}	$g\ m^{-3}\ hr^{-1}$	$g m^{-2}\ hr^{-1}$	hr	^oC	g/m^3	hr^{-1}	$g\ m^{-3}\ hr^{-1}$	$g\ m^{-2}\ hr^{-1}$
8/30/78	406	2.79	19.4	9.1	0.048	0.53	0.19	2.50	19.0	9.1	0.048	0.84	0.29
9/1/78	406	2.79	19.4	9.1	0.051	0.49	0.18	2.50	19.0	9.1	0.051	0.64	0.22
9/2/78	406	2.79	20.1	9.0	0.048	0.47	0.17	2.50	20.1	9.0	0.048	0.69	0.24
9/5/78	405	2.79	21.9	8.4	0.044	0.47	0.17	2.50	21.4	8.5	0.044	0.72	0.25
9/7/78	408	2.79	23.1	8.2	0.040	0.42	0.15	2.50	22.7	8.3	0.040	0.82	0.28
9/11/78	408	2.79	23.1	8.2	0.0415	0.39	0.14	2.50	22.9	8.2	0.0415	0.81	0.28
9/13/78	405	2.79	18.0	9.2	0.051	0.45	0.16	2.50	17.6	9.3	0.051	0.67	0.23
9/20/78	408	2.79	16.0	9.6	0.045	0.35	0.13	2.50	15.5	9.7	0.045	0.60	0.21
9/29/78	406	2.79	14.5	9.8	0.039	0.32	0.12	2.50	14.0	9.9	0.039	0.42	0.15
10/8/78	407	2.79	10.5	10.2	0.040	0.27	0.10	2.50	9.9	10.35	0.040	0.35	0.12

t_r = residence time

T = water temperature

C_s = saturation D.O. concentration

K_2 = surface exchange coefficient

R = total community respiratory rate

h = mean depth

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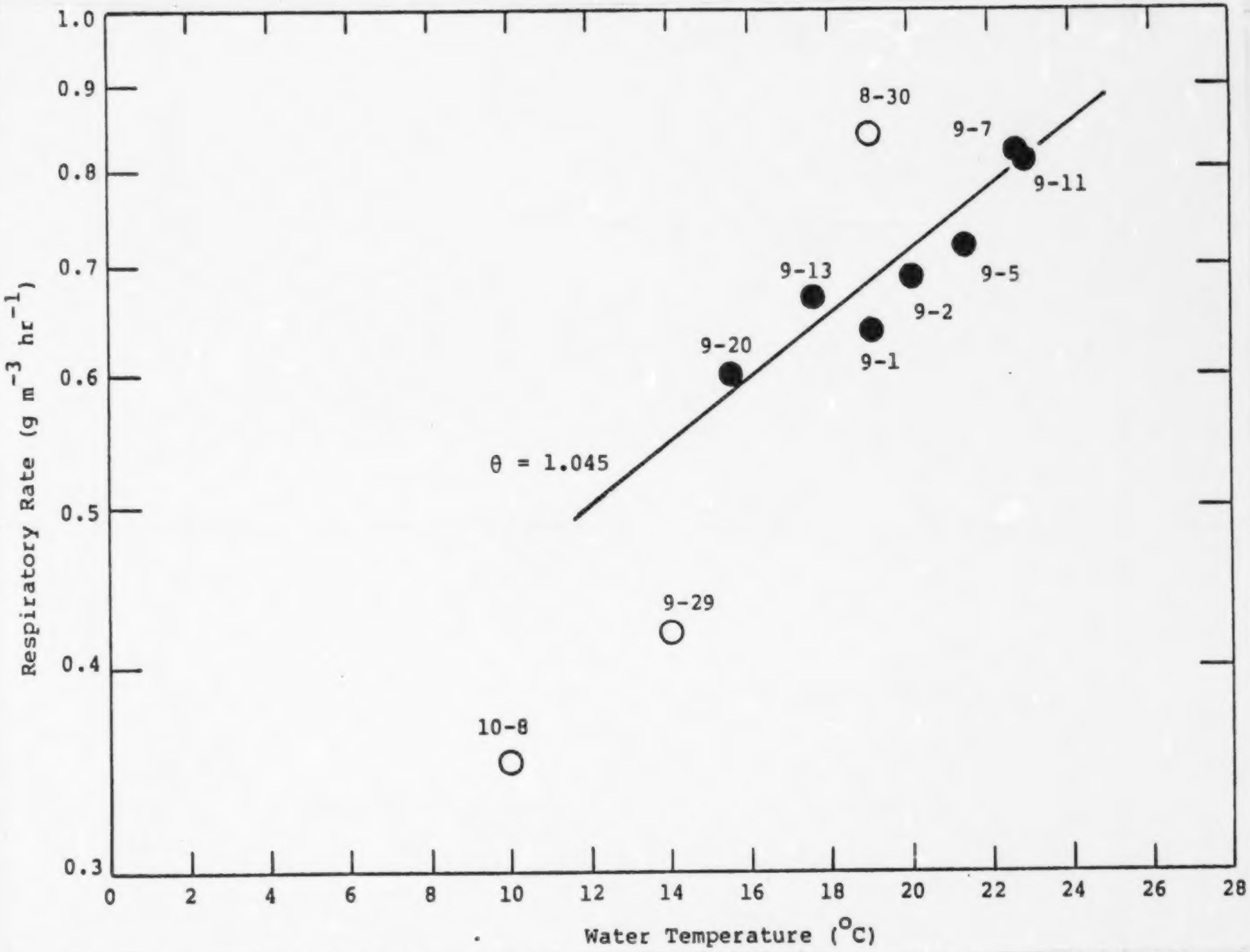

Fig. 6.5. Total community respiratory rate in unshaded section versus water temperature. All values are determined from predawn longitudinal dissolved oxygen surveys. Survey date is given with each respiratory rate. θ-value is determined from data during a short time interval (9-1 to 9-20) when community biomass was assumed to be constant.

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is believed to be an outlier because it was the first set of measurements taken and the procedure was not yet standardized.)

One aspect in favor of plotting R versus T as shown in Fig. 6.5 is the increase in water temperature from 9/1 to 9/11 and the subsequent decrease for the rest of the season. If the community biomass had decreased significantly from 9/1 through 9/20, the 9/13 and 9/20 measurements of respiratory rate would be on a lower curve then the 9/1 and 9/2 measurements. In fact, the opposite is true, and the small difference is believed to be a measurement error, since an increase in biomass is unlikely during this portion of the growing season. Later measurements on 9/29 and 10/8 do indicate a decrease in biomass. The best estimate line in Fig. 6.5 gave $\theta = 1.045$, which was used in DORM for diel curve analysis.

Respiration Inhibition Due to Low Dissolved Oxygen Concentration

The Michaelis-Menton relationship (Eq. 6-5) is used in DORM for respiratory inhibition at low D.O. concentration. Only one set of data taken from 7/31 to 8/1 in reach 10-13 of channel 6 where D.O. concentrations were low enough to inhibit respiratory rate. All other diel D.O. measurements were taken in channel reaches further upstream, where D.O. concentrations were always above 4.5 g/m^3 and there was no evidence of respiratory inhibition.

In order to determine C_{KM} for reach 10-13, successive runs of DORM were made for the two consecutive days of diel data. C_{KM} was adjusted until the residuals for the night D.O. routing were minimized. This procedure gave $C_{KM} = 2.3\ g/m^3$, which was used in DORM for reach 10-13. This value was not used for the 6-9 reaches in channels 6, 7, and 8 because respiratory inhibition was unlikely at the D.O. concentrations found in these reaches. $C_{KM} = 0.0$ was used for the diel D.O. measurements of reach 6-9 in channels 6, 7, and 8.

SECTION 7

SENSITIVITY ANALYSIS

The potential errors caused by simplifying assumptions made in diel curve productivity analysis have never been tested. Where surface exchange is not directly measured, estimates of surface exchange coefficient are likely to be poor. In addition, no temperature dependence of respiration ($\theta = 1$) and no inhibition of respiration at low D.O. concentration ($C_{KM} = 0.0$) are often assumed, and longitudinal dispersion is often neglected without assessing its possible contribution. Finally, the means of interpolating a continuous curve between upstream D.O. measurements has never been discussed. This section considers the effect these simplifications would have upon productivity analysis in the MERS field channels. The sensitivity of the results to errors in computed or assumed channel residence time is also studied.

TEMPERATURE

The contribution of the respiration temperature coefficient, θ, may be determined by applying DORM to diel D.O. measurements with $\theta = 1.045$ and $\theta = 1.000$, and comparing the results. This was done for three sets of diel D.O. measurements. Water temperature and respiratory rate computed by DORM are shown in Fig. 7.1. Total daily respiration computed on 6/27/79 was reduced 7 per cent by assuming $\theta = 1.000$. Greater errors in R could be expected with larger diel temperature fluctuations than in Fig. 7.1.

An increase in R will also increase the value of P computed by DORM, and vice versa. This is shown to occur in Figs. 7.2, 7.3 and 7.4, where values of P computed by DORM over the day are plotted against photosynthetically active radiation (PAR). Including a temperature dependence for R changed the computed magnitude of P ($\simeq 3\%$) but did not significantly change any hysteresis in the P versus PAR curve.

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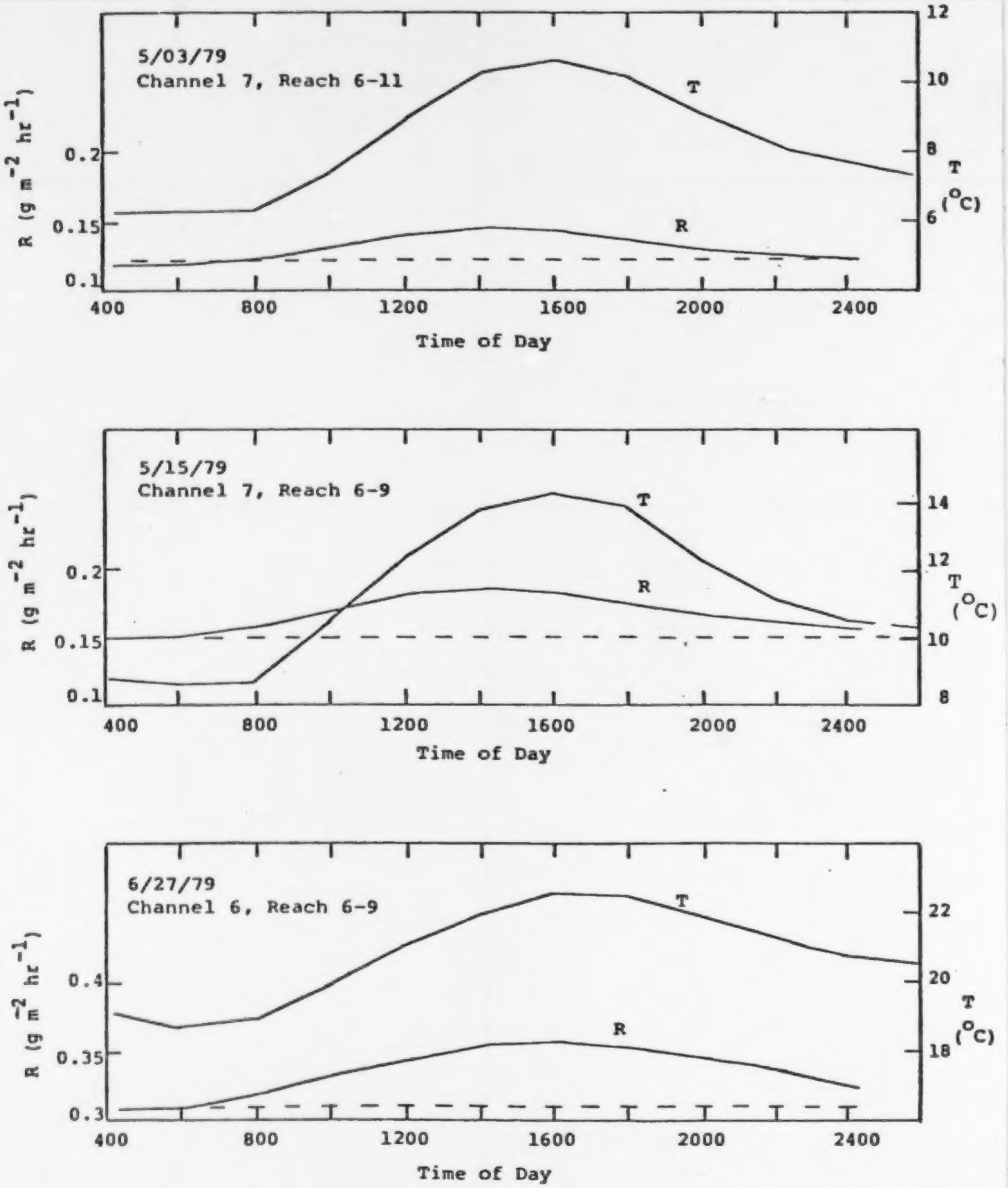

Fig. 7.1. Measured water temperature (T) and total community respiratory rate (R) computed by DORM for three sets of diel D.O. measurements. Solid line: $\theta = 1.045$ (respiration dependent upon temperature). Dashed line: $\theta = 1.000$ (respiration assumed to be constant).

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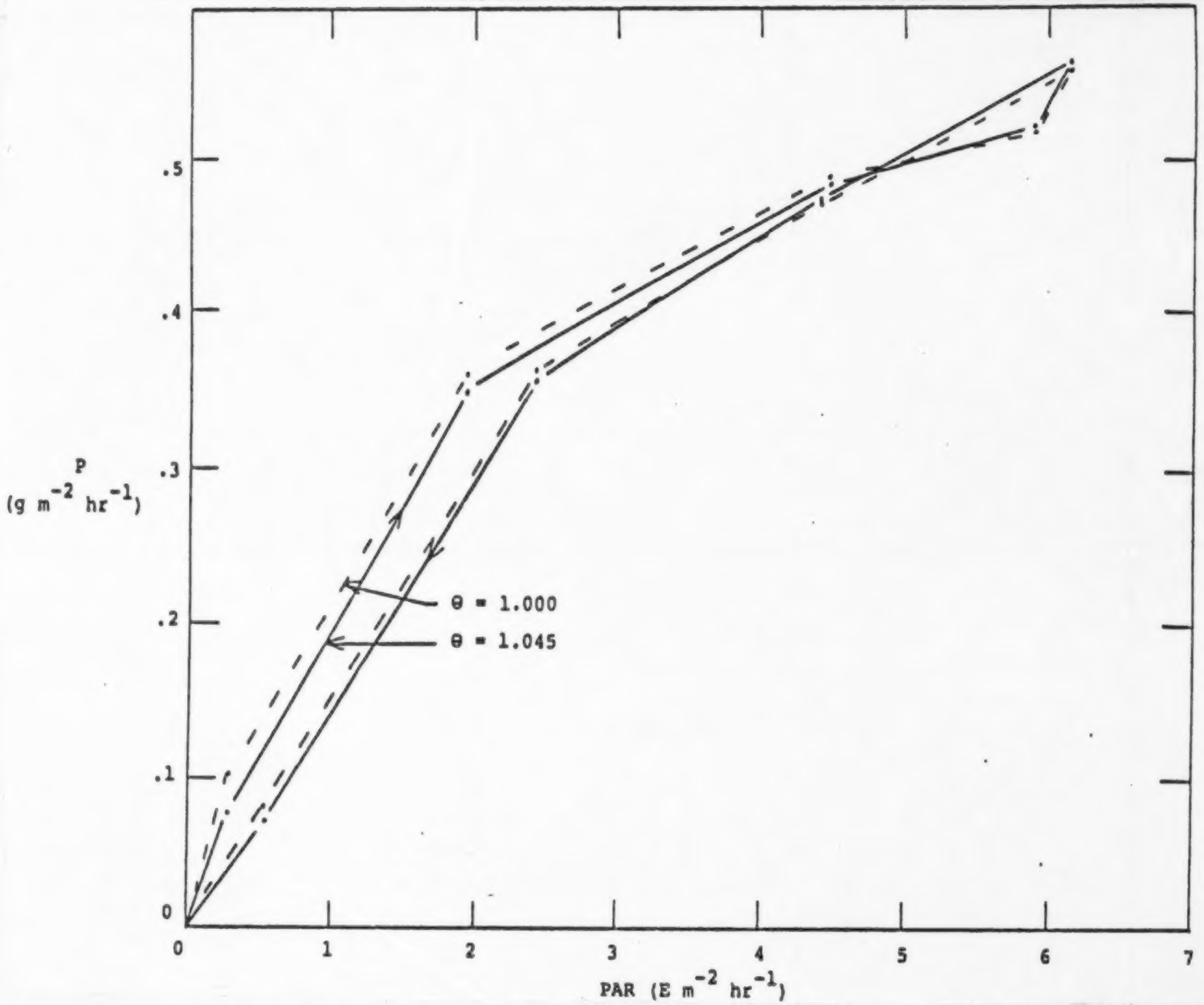

Fig. 7.2. Total community photosynthesis rate (P) computed by DORM versus measured photosynthetically active radiation for $\theta = 1.045$ (solid line) and $\theta = 1.000$ (dashed line). May 3, 1979, Channel 7, reach 6-11.

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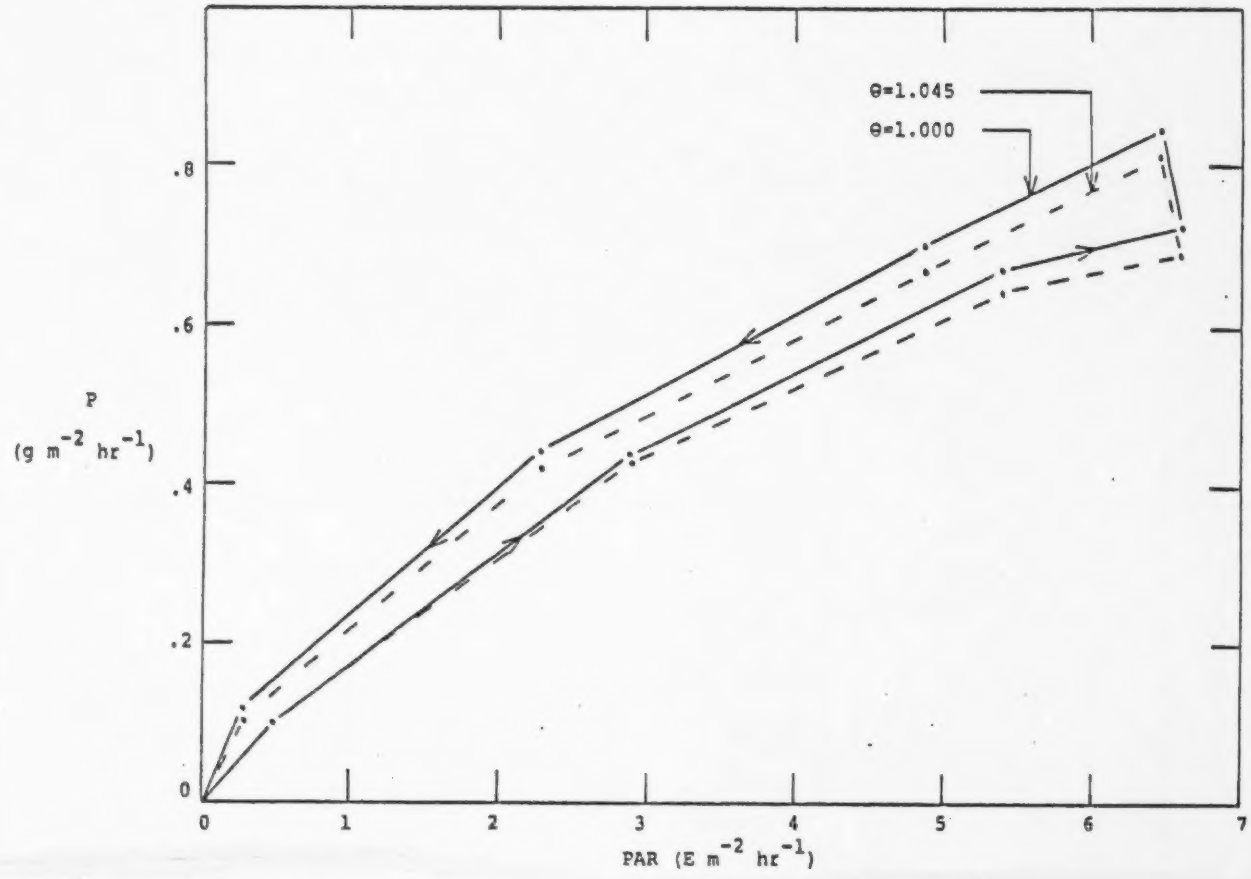

Fig. 7.3. Total community photosynthetic rate (P) computed by DORM versus measured photosynthetically active radiation for θ = 1.45 (solid line) and θ = 1.000 (dashed line). May 15, 1979, Channel 7, reach 6-9.

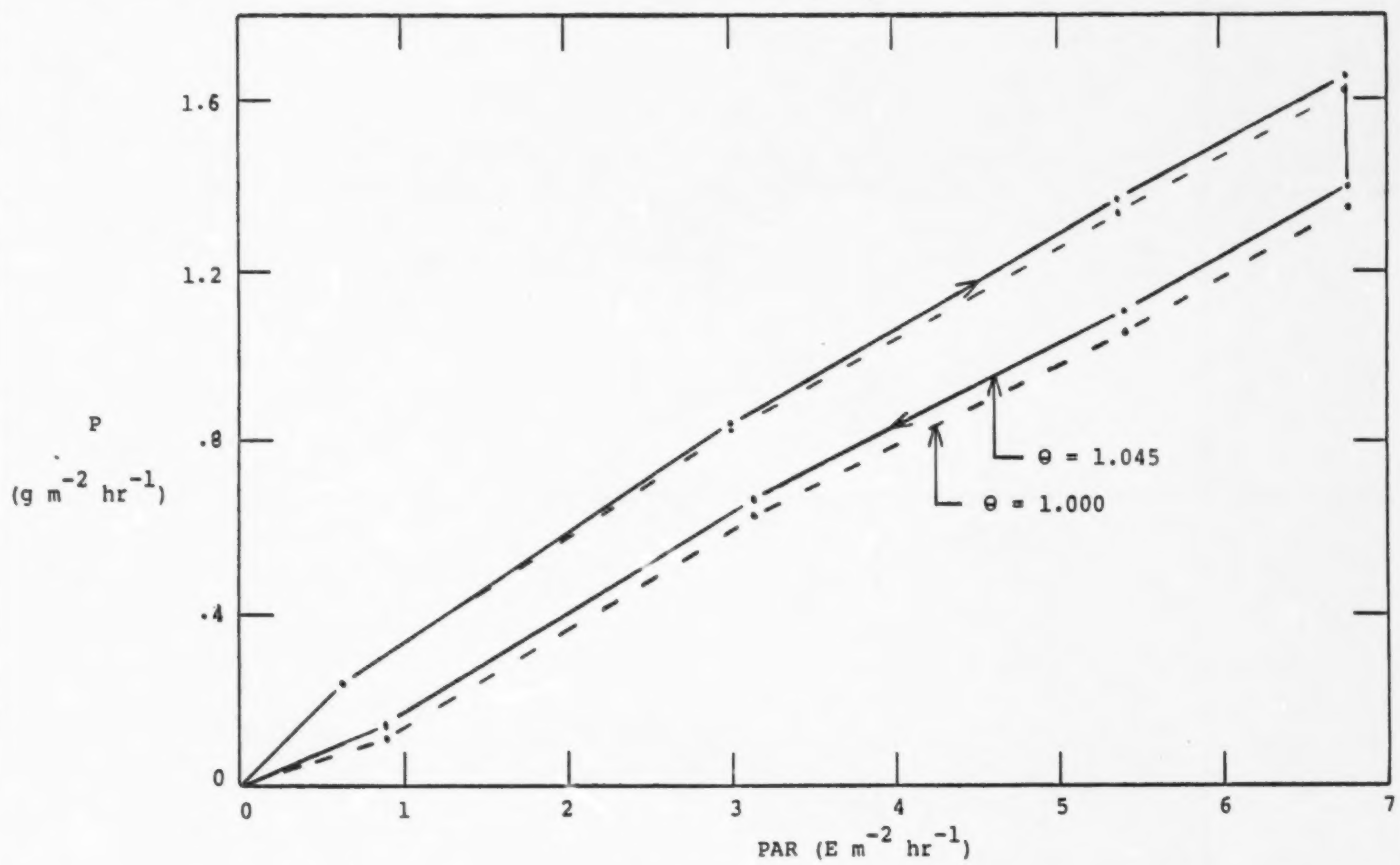

Fig. 7.4. Total community photosynthetic rate (P) computed by DORM versus measured photosynthetically active radiation for $\theta = 1.045$ (solid line) and $\theta = 1.000$ (dashed line). June 27, 1979, Channel 6, reach 6-9.

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RESPIRATION INHIBITION AT LOW D.O. CONCENTRATION

Respiratory rate is strongly affected by very low dissolved oxygen concentration. Failure to account for this relationship can greatly alter the results of diel curve analysis. Dissolved oxygen measurements were taken for two consecutive days in a channel reach which encountered low D.O. concentration (channel 6, reach 10-13). Diel curve analysis was performed with $C_{KM} = 2.3\ g/m^3$ and $C_{KM} = 0.0$. The temporal variation in P, R, and downstream D.O. concentration is given for both cases in Fig. 7.5, which shows the increase in respiratory rate caused by higher D.O. concentration during the day. Photosynthesis production rates are, in turn, larger with $C_{KM} = 2.3\ g/m^3$, because the larger R values during daylight hours must be countered with larger computed photosynthetic rates P to give the same P-R value derived by DORM from the measured D.O. concentration.

Figures 7.6 and 7.7 compare P versus PAR curves with $C_{KM} = 0.0$ and $C_{KM} = 2.3$ for each of the two diel D.O. measurement days. Both days exhibited significant hysteresis of the P versus PAR curves. It is interesting to note that the hysteresis was counter-clockwise on 7/31/79 and clockwise on 8/1/79. Including $C_{KM} = 2.3\ g/m^3$ in the analysis reduced clockwise hysteresis and increased counter-clockwise hysteresis. It did not, however, eliminate hysteresis in either case. The possible reasons for the hysteresis of the P versus PAR curves will be discussed in Section 8.

SURFACE EXCHANGE

The rate of oxygen surface exchange can vary greatly from one stream to another, and inclusion of surface exchange is often very important for meaningful diel curve analysis. Dissolved oxygen surface exchange is generally the largest when photosynthetic rates are the highest, so the greatest error occurs near the peak of the P versus PAR curve. In the MERS field channels, the surface exchange coefficient is smaller than in many natural streams and yet inaccurate surface exchange rates can significantly alter the results of diel curve analysis of these channels.

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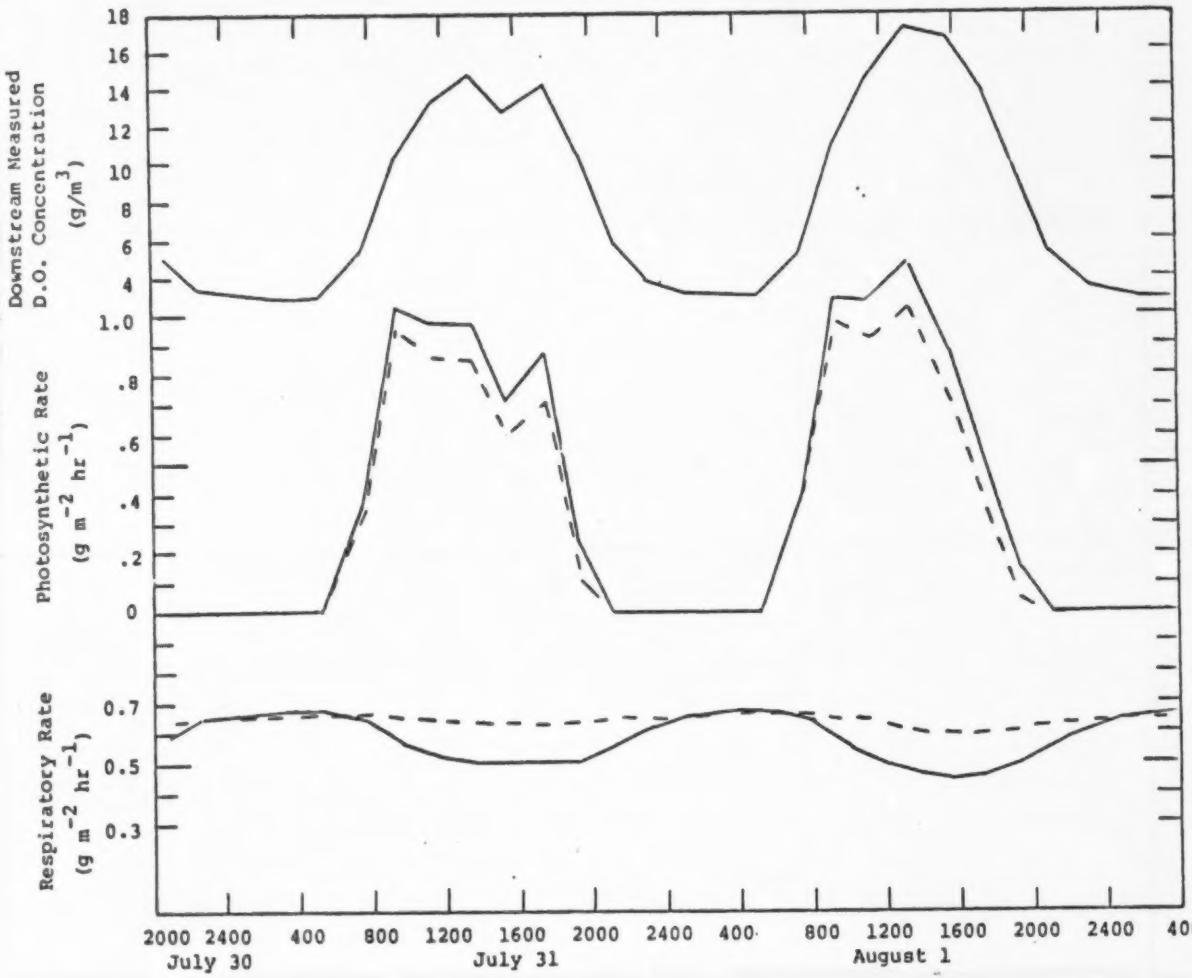

Fig. 7.5. Comparison of total community photosynthetic and respiratory rates computed by DORM with and without respiratory inhibition at low D.O. concentration. Solid line: $C_{KM} = 2.3\ g/m^3$. Dashed line: $C_{KM} = 0.0$.

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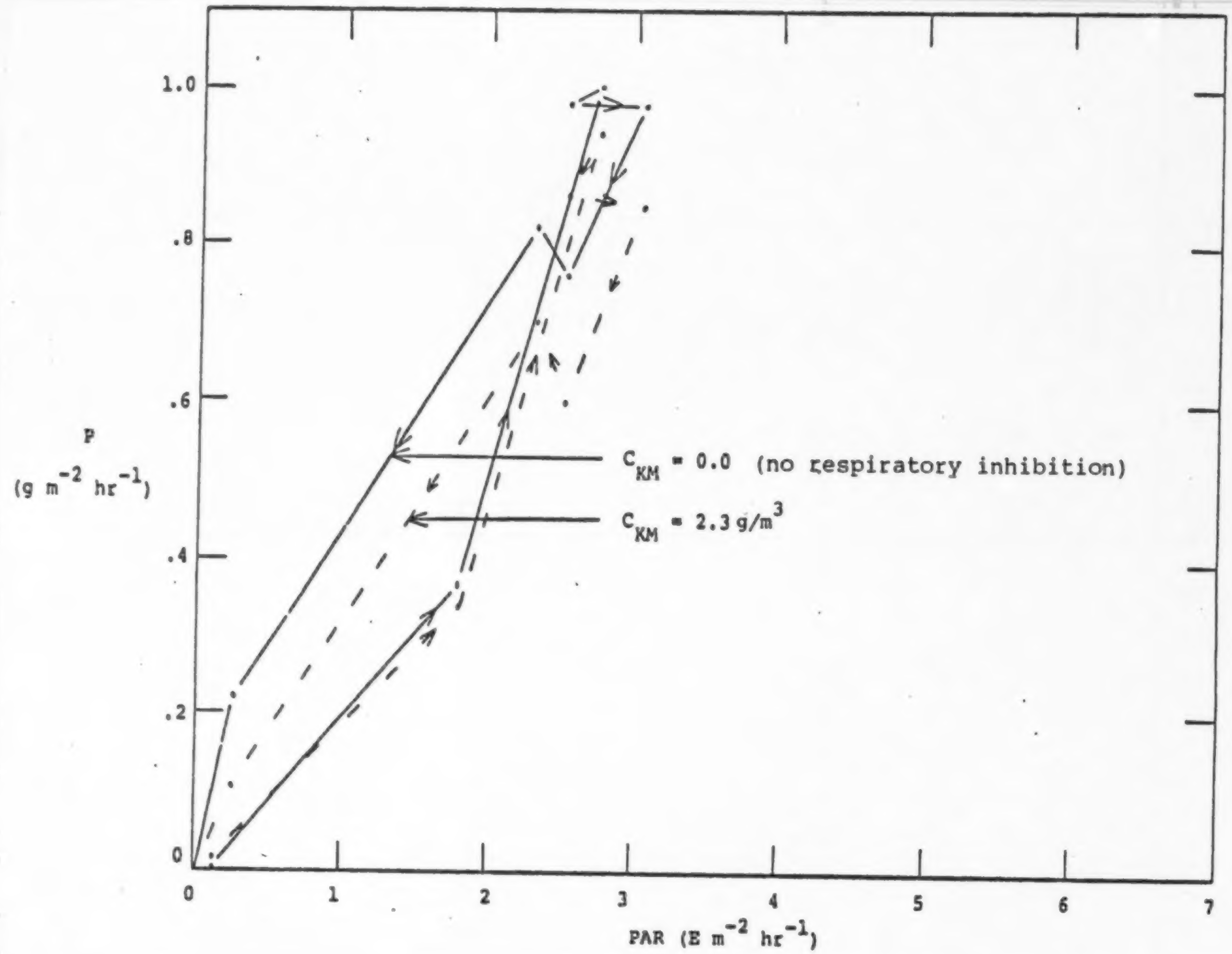

Fig. 7.6. Total community photosynthetic rate computed by DORM versus measured photosynthetically active radiation (PAR) with and without respiratory inhibition at low D.O. concentration. July 31, 1979, Channel 6, reach 10-13.

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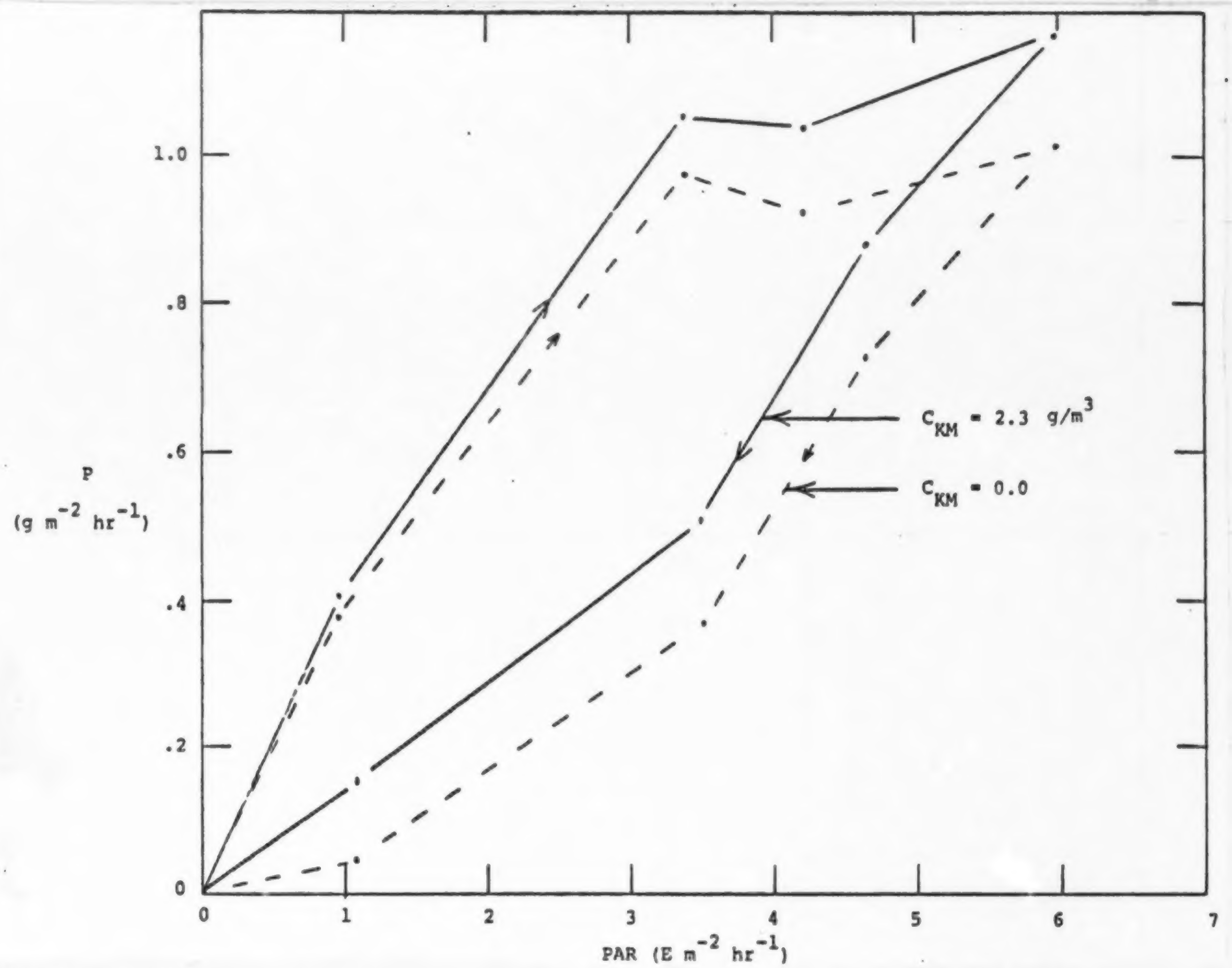

Fig. 7.7. Total community photosynthetic rate computed by DORM versus measured photosynthetically active radiation (PAR) with and without respiratory inhibition at low D.O. concentration. August 1, 1979, Channel 6, reach 10-13.

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DORM was used on two sets of diel D.O. measurements to perform diel curve analysis with and without surface exchange. The results for a day with low wind velocity are shown in Fig. 7.8. Exclusion of surface exchange in the analysis reduced total daily photosynthetic production (TP) by 8 per cent and reduced total daily respiration (TR) by 16 per cent. The P versus PAR curves in Fig. 7.9 indicate that exclusion of surface exchange will increase clockwise hysteresis. The contribution of surface exchange to diel curve analysis increases with wind because wind waves increase surface exchange coefficient. This is shown in Fig. 7.10. Excluding the effect of surface exchange during a windy day has the effect of decreasing the peak photosynthetic production rate by 18 per cent, total daily photosynthetic production by 20 per cent, and total daily respiration by 15 per cent. The P versus PAR curves given in Fig. 7.11 indicate that exclusion of surface exchange from the analysis for this day changed a curve with almost no hysteresis into one with significant clockwise hysteresis.

CURVE FITTING TO UPSTREAM D.O. MEASUREMENTS

Two station diel curve analyses require a continuous curve of upstream D.O. concentration. The upstream D.O. measurements, however, are at finite time intervals and a continuous curve must be interpolated between data points. Often the curve is drawn by hand or a linear interpolation is used. DORM was formulated so that a polynomial of any order, NOR, can be fitted through each of the upstream D.O. measurements (section 5). Therefore, if a linear interpolation is inaccurate, a higher order interpolation may be used. The upstream D.O. concentration computed by DORM with first order, third order, and fifth order curves between data points is given in Figs. 7.12 and 7.13 for channel 6, reach 10-13. Although the diel variation in upstream D.O. concentration was large for this reach, there is only a small difference between the first and third order curves, and an insignificant difference between the third and fifth order curves. The P versus PAR curves for 7/31 and 8/1 were nearly identical for NOR=1, 3, and 5. Finally, increasing the value of NOR from 1 to 3 decreased the computed total daily photosynthetic production and total daily respiration by only 2 per cent for both days. All of this indicates that for most diel D.O. measurements with time intervals of two hours or less, the linear interpolation between measurements is sufficiently accurate.

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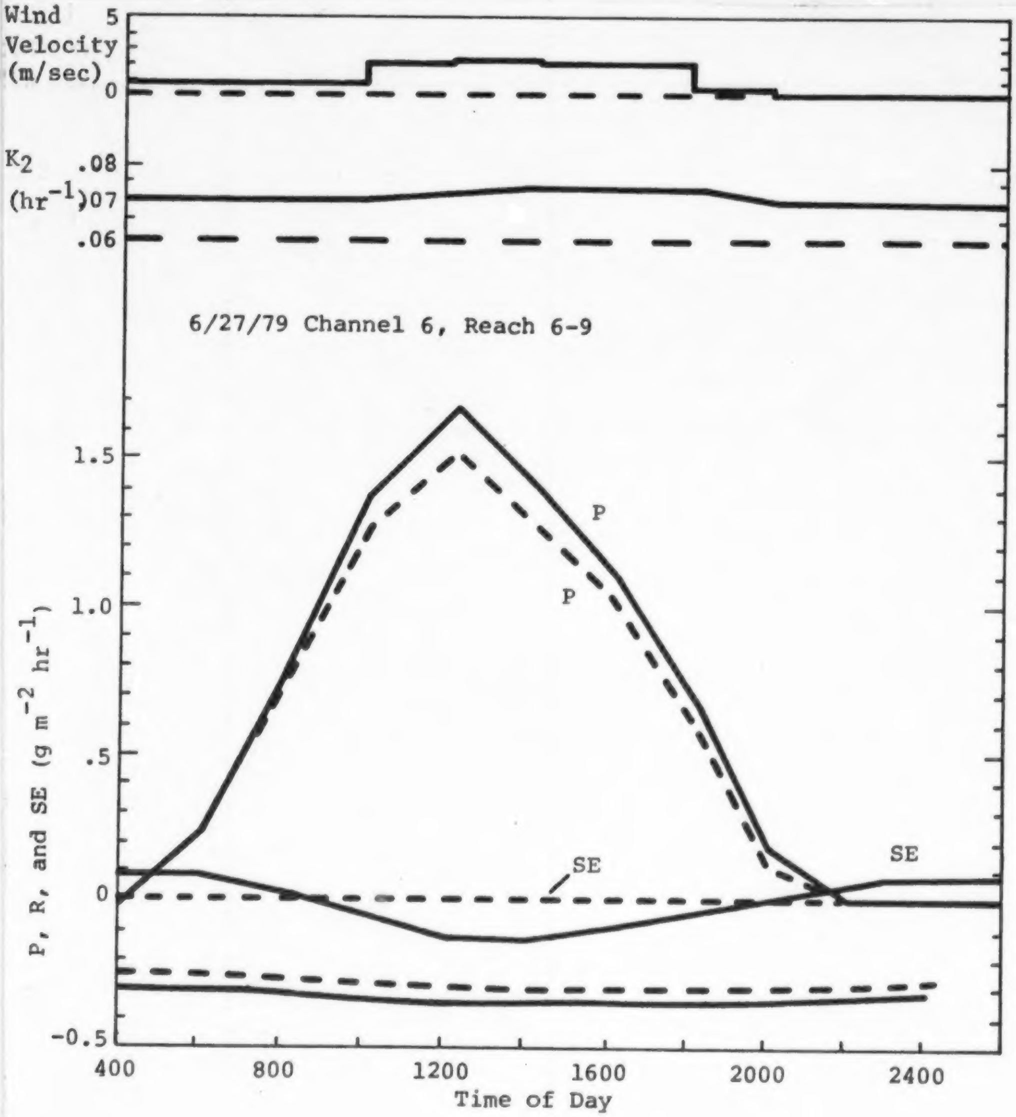

Fig. 7.8. Total community photosynthetic (P) and respiratory (R) rates with and without D.O. surface exchange (SE) as computed by DORM. Dashed line indicates values without surface exchange. July 27, 1979, Channel 6, Reach 6-9.

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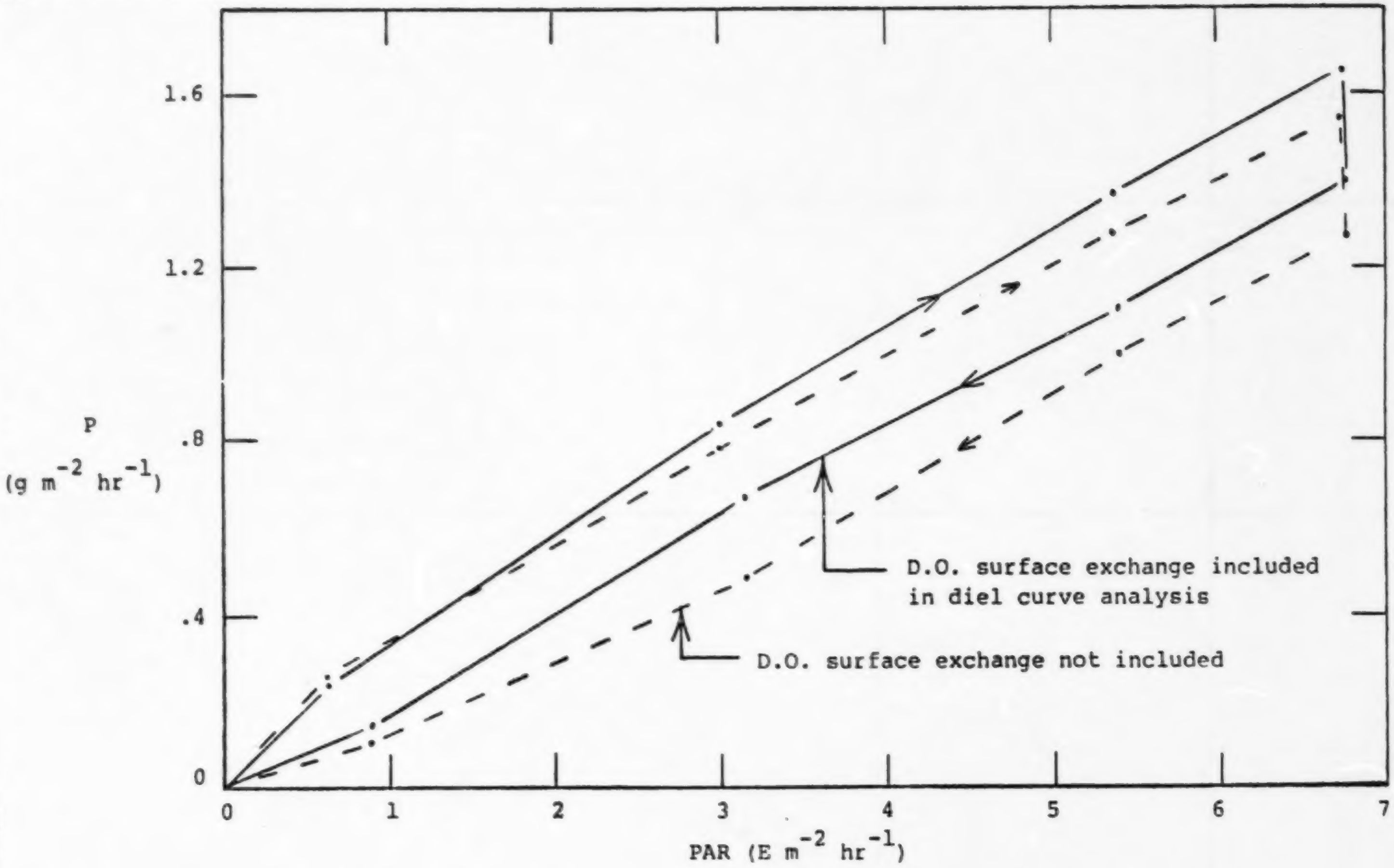

Fig. 7.9. Total community photosynthetic rate computed by DORM versus measured photosynthetically active radiation (PAR) including and excluding D.O. surface exchange for channel 6, reach 6-9, June 27, 1979.

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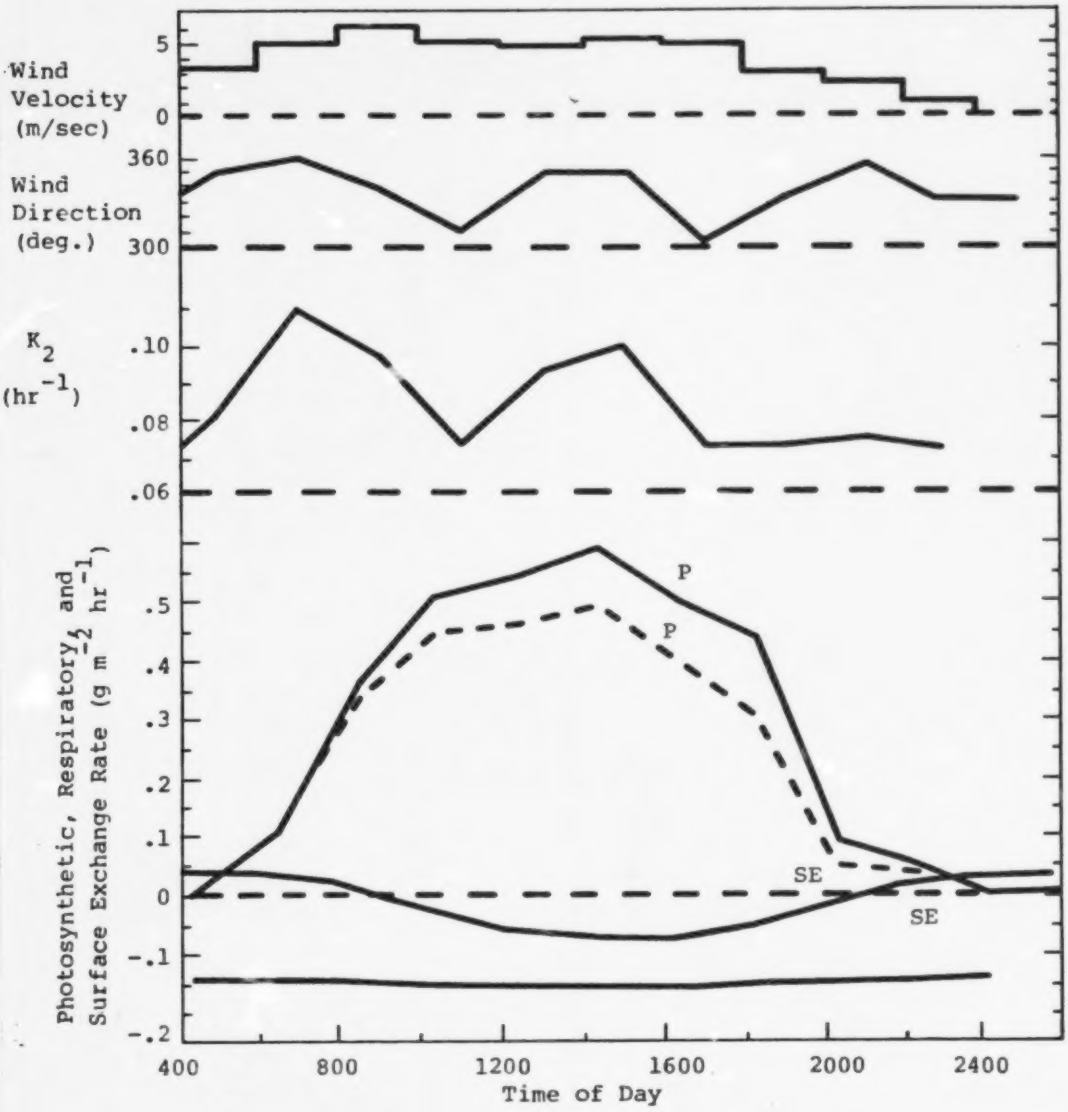

Fig. 7.10. Total community photosynthetic (P) and respiratory (R) rates with and without D.O. surface exchange (SE) as computed by DORM. Channel 7, reach 6 → 1, 5/03/79. Dashed line indicates values without surface exchange.

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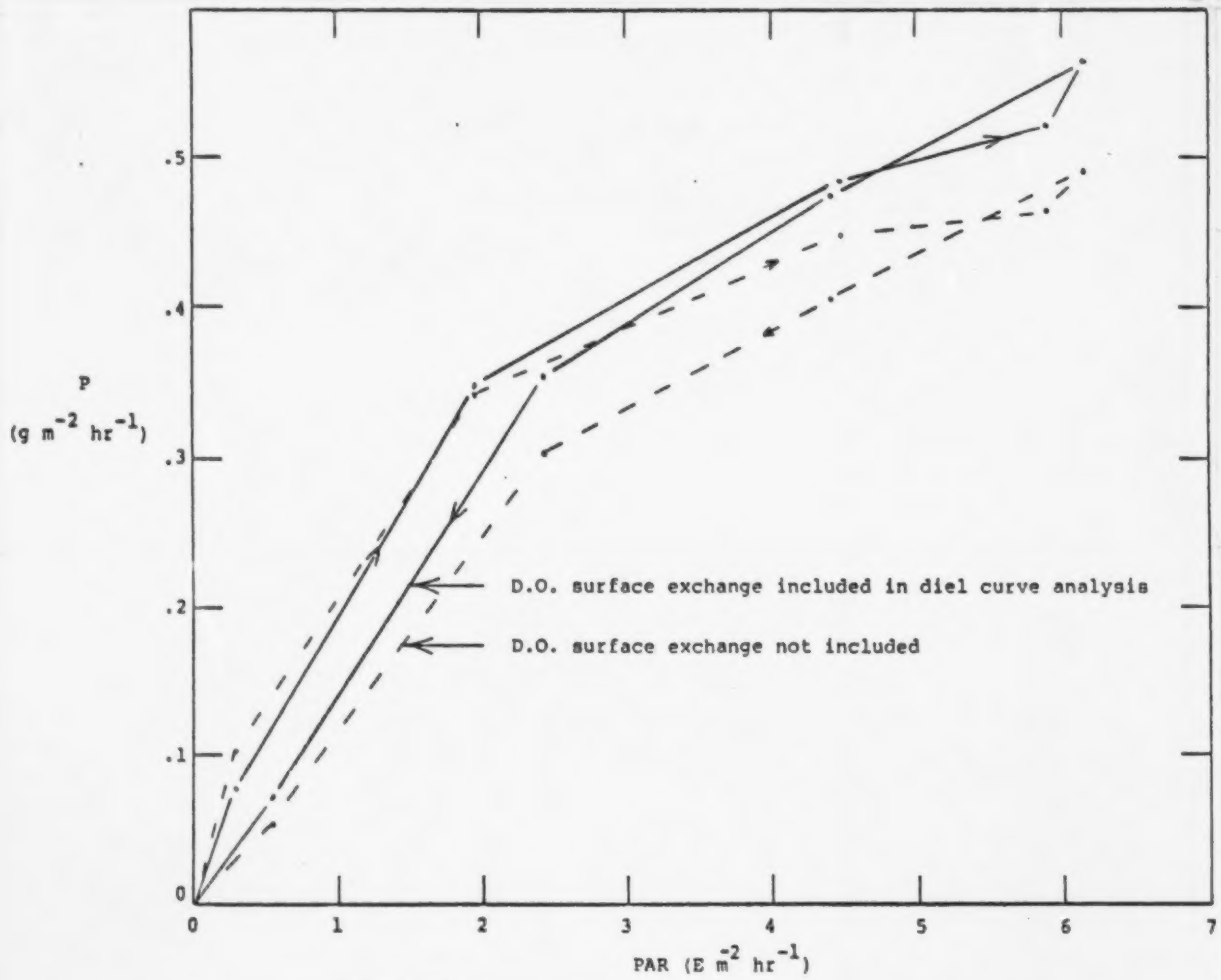

Fig. 7.11. Total community photosynthesis (P) computed by DORM versus measured photosynthetically active radiation (PAR) including and excluding D.O. surface exchange for channel 7, reach 6-11, May 3, 1979.

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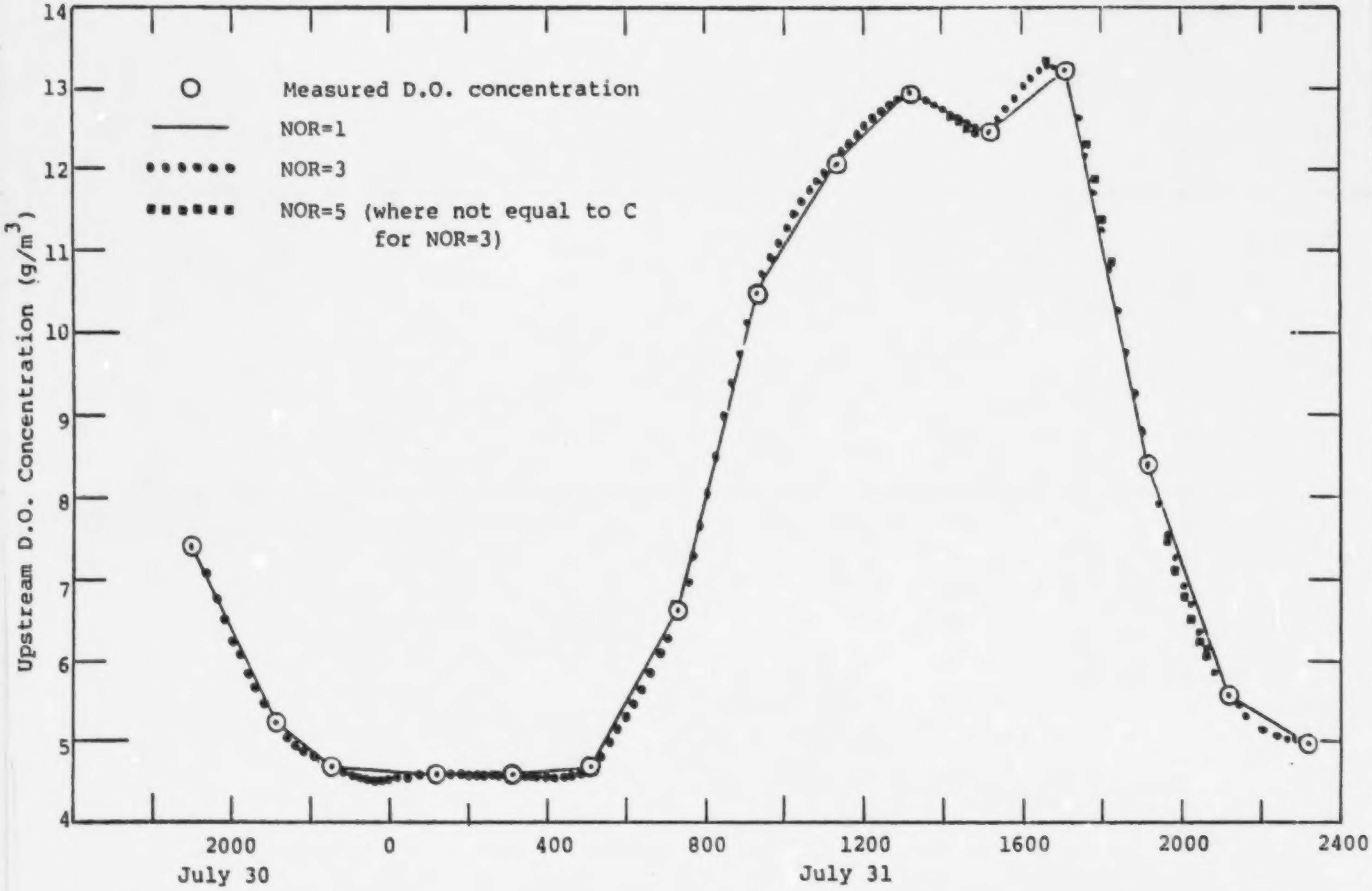

Fig. 7.12. Measured upstream dissolved oxygen concentration and interpolation between data points with first, third, and fifth order curves for channel 6, reach 10-13, July 30-31, 1979.

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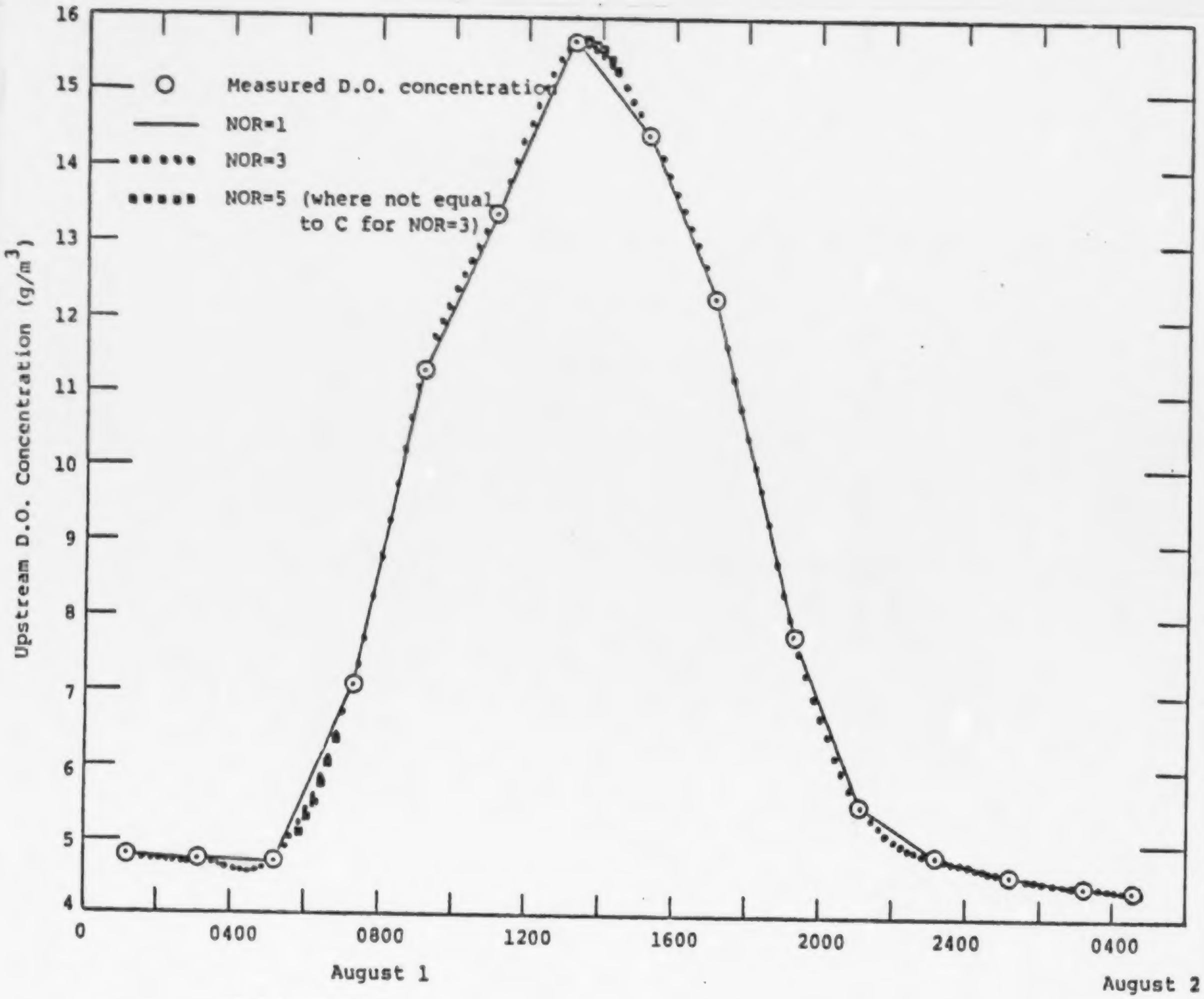

Fig. 7.13. Measured upstream dissolved oxygen concentration and interpolation between data points with first, third, and fifth order curves for channel 6, reach 10-13, August 1-2, 1979.

RESIDENCE TIME

Since total community photosynthesis and respiration are computed as rates of production and uptake, it is logical that the results of diel curve analysis are very sensitive to the hydraulic residence time of the channel reach. The effect of errors in residence time were determined by running DORM with flow rates 20 per cent above or below that which was measured. In Fig. 7.14 an increase of 20 per cent in residence time is shown to eliminate a moderate counterclockwise hysteresis in the P versus PAR curve. This means that a 20 per cent error in stream reach hydraulic residence time can create a moderate hysteresis in the P versus PAR curve developed from diel curve analysis. As could be expected, the magnitude of P increases proportionally with decreasing residence time. A somewhat larger clockwise P versus PAR hysteresis was reduced but not eliminated by a 20 per cent decrease in residence time for the diel curve analysis shown in Fig. 7.15. When channel reach hydraulic residence time was increased or decreased by 20 per cent, a change of approximately 16 per cent in total daily respiration and of approximately 17 per cent in total daily photosynthetic production was computed by DORM for both sets of diel D.O. measurements. It should be noted that a 20 per cent error in residence time is very large. A review of field records indicates that the maximum probable error in hydraulic residence time estimates for the MERS channels during the diel D.O. measurements is about 13 per cent.

LONGITUDINAL DISPERSION

There is much less longitudinal dispersion in the MERS field channels than in most natural streams because the channels are very narrow. Consequently, longitudinal dispersion had no effect upon diel curve analysis in the MERS field channels. This would not be true for all streams, however. Fischer (1973) lists measured longitudinal dispersion coefficients (D_L) for natural streams and, although they vary greatly, a typical low value would be 5 m^2/sec. By contrast, D_L in the MERS field channels as measured by Stefan et al (1980) is approximately 0.04 m^2/sec. Consider that a diel curve analysis is being performed on a hypothetical stream with a longitudinal dispersion coefficient of 5 m^2/sec but with all of the other properties of a MERS channel. The

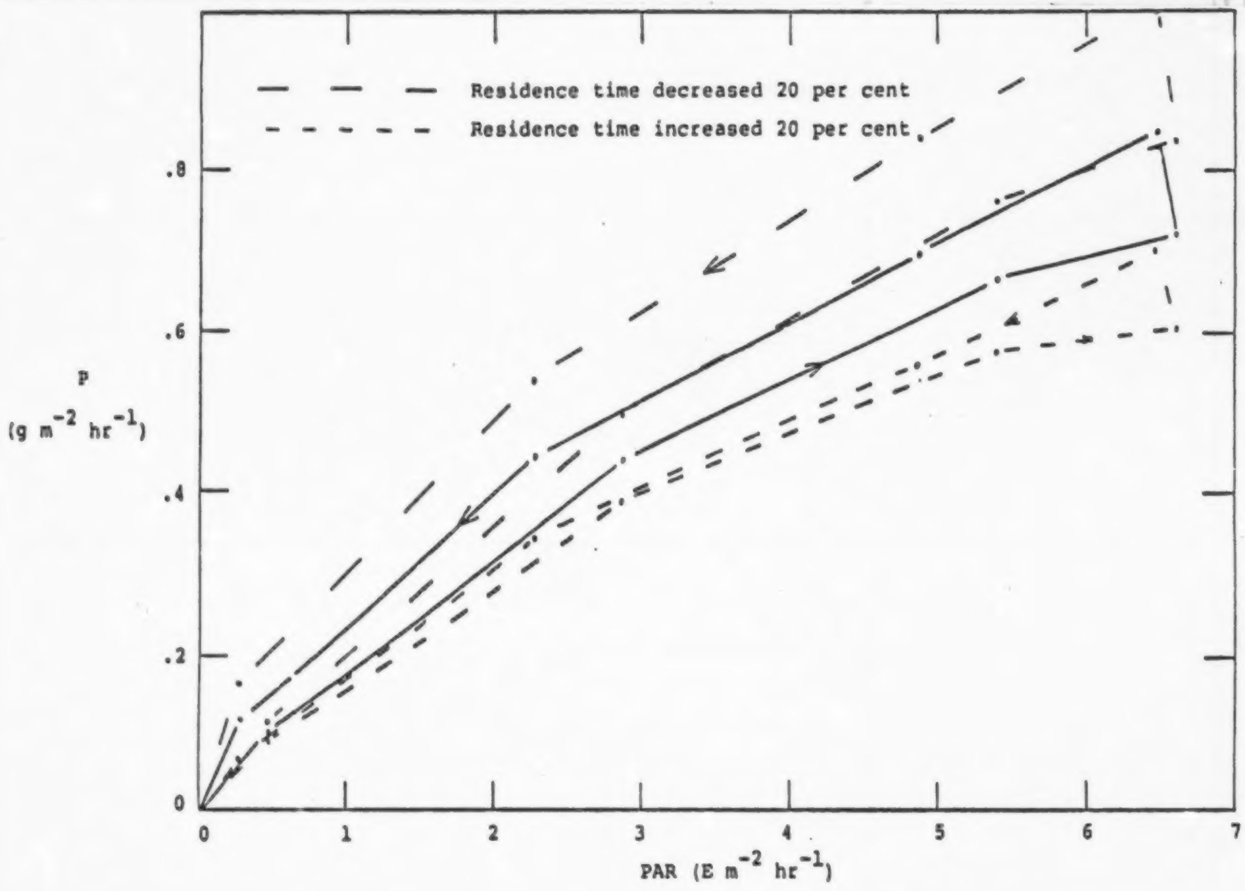

Fig. 7.14. Total community photosynthetic production computed by DORM versus photosynthetically active radiation with channel reach hydraulic residence time as measured, increased by 20 per cent, and decreased by 20 per cent for channel 7, reach 6 → 9, May 25, 1979.

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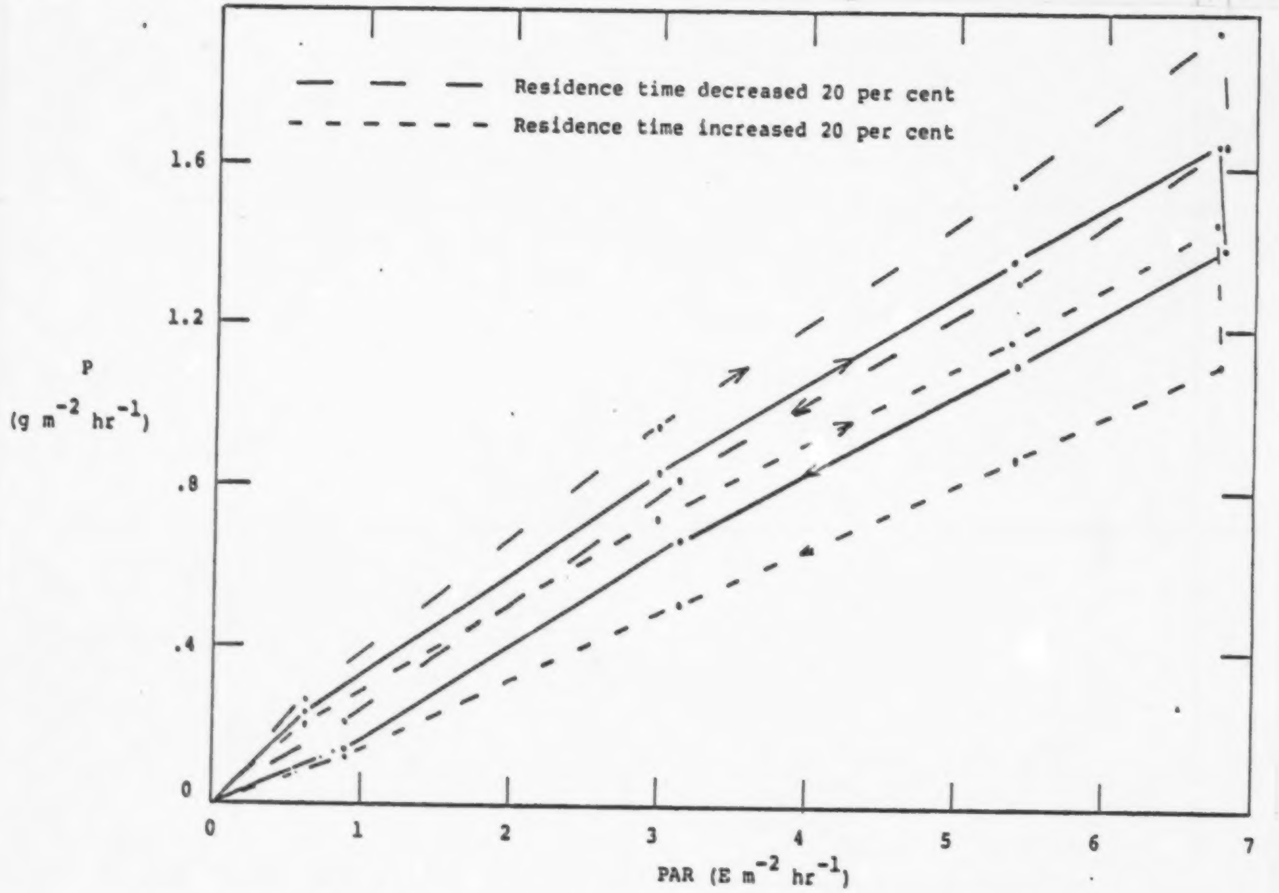

Fig. 7.15. Total community photosynthetic production computed by DORM versus photosynthetically active radiation with channel reach hydraulic residence time as measured, increased by 20 per cent, and decreased by 20 per cent for channel 6, reach 6 → 9, June 27, 1979.

temporal variation of photosynthetic and respiratory rates for D_L = 0.04 m^2/s and 5.0 m^2/sec are compared in Fig. 7.16 for one set of diel D.O. data. The difference is the greatest when the term $\partial(D_L\ \partial C/\partial x)\partial x$ is large (in mid-afternoon). Figure 7.16 indicates that, for a more highly dispersive stream, neglecting longitudinal dispersion would significantly reduce computed photosynthetic production rates (10 per cent in this example). Figure 7.17 indicates that neglecting longitudinal dispersion would increase clockwise hysteresis in the P versus PAR curve.

SUMMARY OF POTENTIAL ERRORS IN DIEL CURVE PRODUCTIVITY ANALYSIS

The relative contribution of the potential errors in diel curve analysis may be seen by comparing the results of one day's diel D.O. data. Table 7.1 lists the per cent error in total daily respiration, photosynthesis, and P/R ratio caused by selectively excluding parameters in diel curve analysis for channel 6, reach 6-9, June 27, 1979. The largest errors are caused by neglecting D.O. surface exchange and by the use of an incorrect residence time.

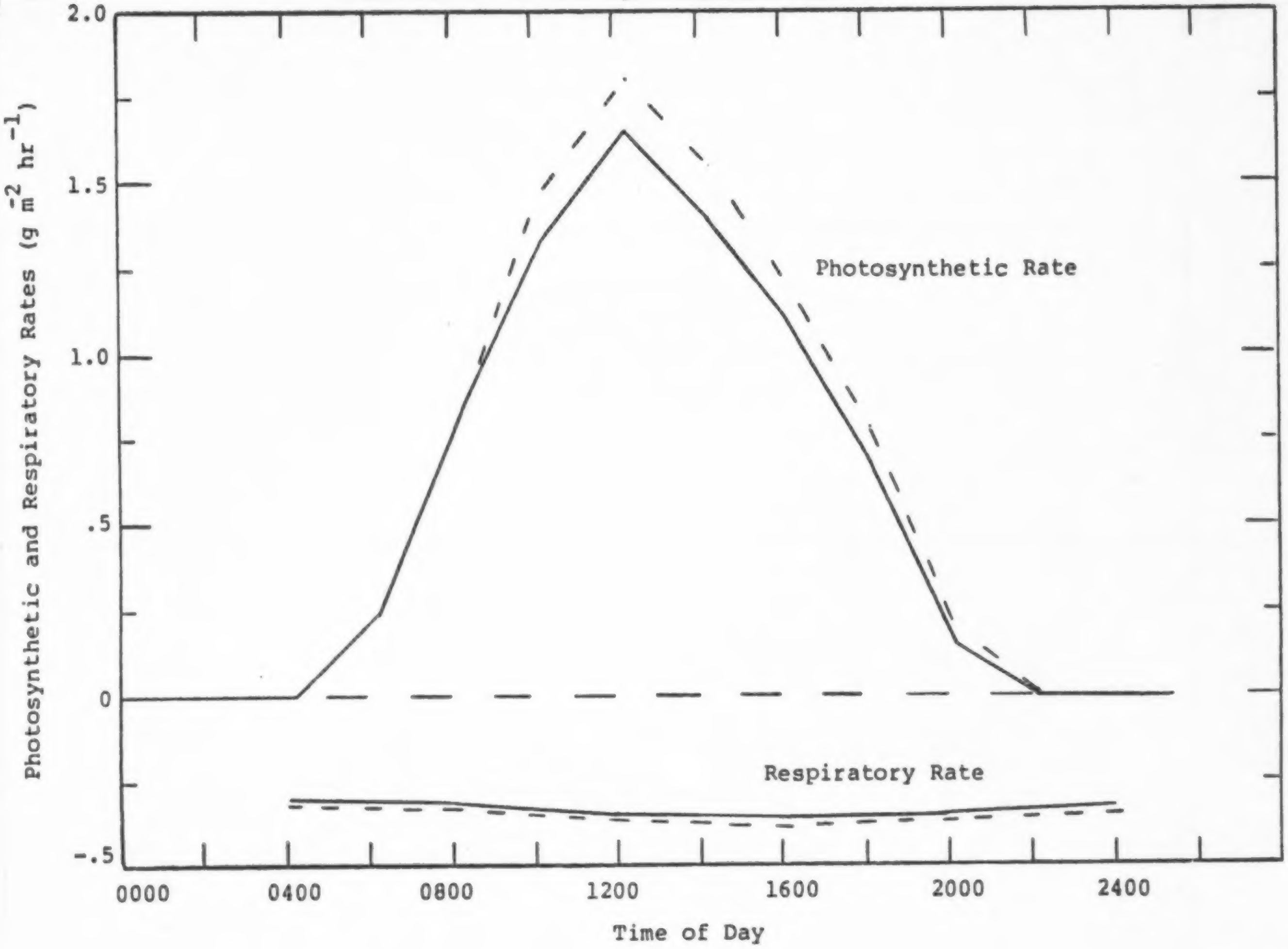

Fig. 7.16. Comparison of total community photosynthetic (P) and Respiratory (R) rates computed by DORM with two longitudinal dispersion coefficients (D_L). Solid line: D_L = 0.04 m^2/sec. Dashed line: D_L = 5 m^2/sec.

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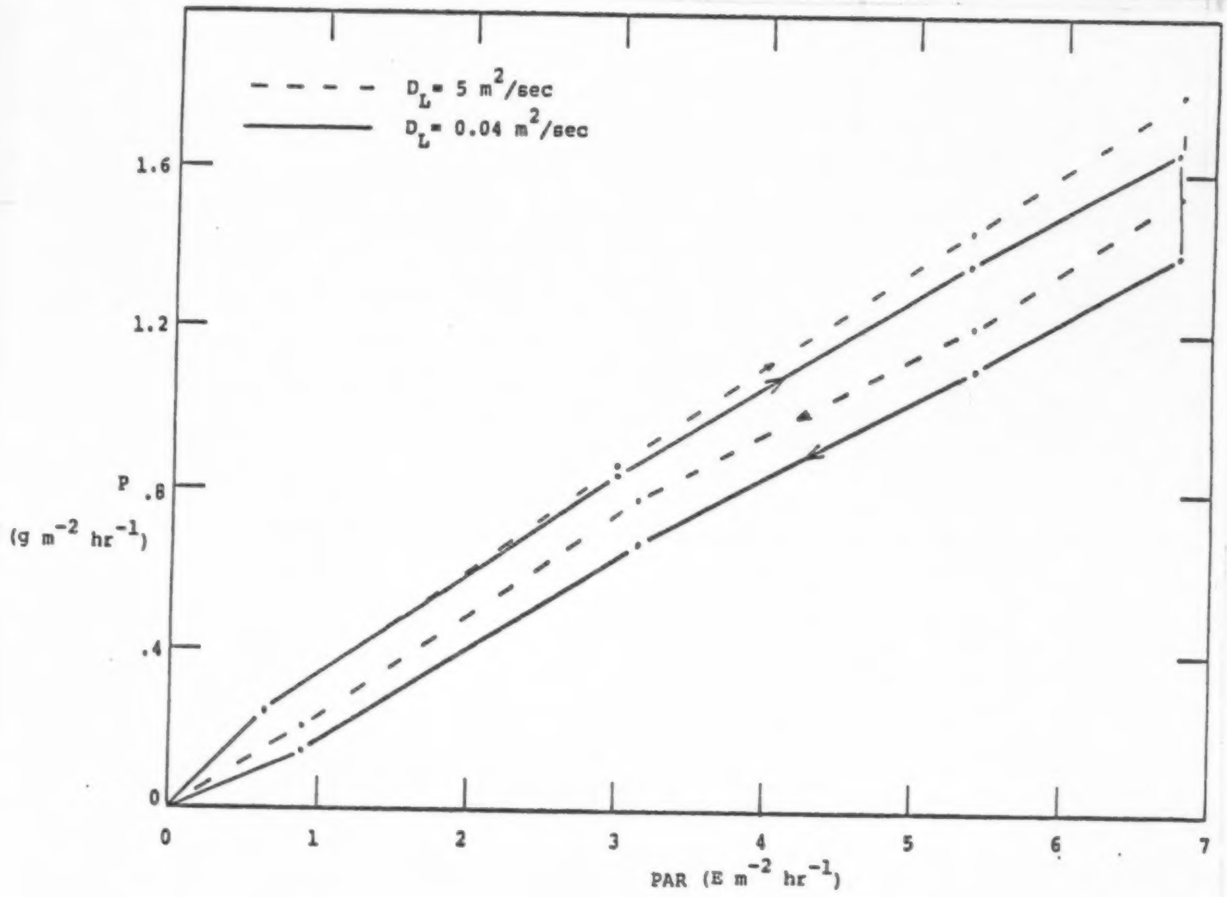

Fig. 7.17. Total community photosynthetic production rate (P) computed by DORM versus photosynthetically active radiation (PAR) at two longitudinal dispersion coefficients using diel D.O. data from channel 6, reach 6 → 9, June 27, 1979.

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TABLE 7.1. PER CENT ERROR IN TOTAL DAILY RESPIRATION, TOTAL DAILY PHOTOSYNTHESIS, AND P/R RATIO CAUSED BY SPECIFIC PARAMETER CHANGES IN DORM FOR DIEL CURVE ANALYSIS (CHANNEL 6, REACH 6-9, JUNE 27, 1979)

		Total Daily Respiration	Total Daily Photosynthesis	P/R Ratio
		(g/m^2)	(g/m^2)	
	Values computed by DORM using best estimates of all parameters	8.01	14.79	1.85
	Parameter change in DORM:	Per Cent Error	Per Cent Error	Per Cent Error
1.	θ reduced from 1.045 to 1.000	-7	-3	4
2.	D.O. surface exchange neglected	-16	-8	9
3a.	Flow rate reduced 20% (increase residence time)	-17	-18	-2
3b.	Flow rate increased 20% (decrease residence time)	17	18	1
4.	NOR reduced from 3 to 1	1	0.4	0
5.	D_L increased from 0.04 to 5.0 m^2/sec	5	10	-3
6.	Combination of No. 1, 2, and 4 to give graphical method for diel curve analysis	-18	-9	10

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SECTION 8

APPLICATION OF DORM TO STREAM PRODUCTIVITY ANALYSIS

COMPARISONS BETWEEN THE NUMERICAL ROUTING PROCEDURE (DORM) AND THE SIMPLIFIED GRAPHICAL PROCEDURE

Use of the complete D.O. transport equation such as applied in DORM requires more data preparation, time and effort than the simplified graphical procedure. For fast estimates of P and R an investigator will be tempted to use the graphical procedure. Both procedures were applied to the data obtained in the MERS channels in 1978 and 1979, and it is therefore possible to present a comparison. It is implied that computer routing with the complete DORM gives the most accurate results because it makes the least assumptions.

The graphical procedure for diel curve productivity analysis which was described in Section 5 assumes that there is no longitudinal dispersion ($D_L = 0$), no change of respiration with temperature ($\theta = 1.000$), no respiratory inhibition due to low D.O. concentration ($C_{KM} = 0.0$), and no surface exchange of oxygen ($K_2 = 0$). In addition, a linear interpolation between upstream D.O. measurements is used (NOR=1). Graphical procedures which include surface exchange in an approximate manner and a hand-drawn curve through the upstream D.O. measurements have been described by Odum (1956) and Edwards and Owens (1962). The "graphical procedure" compared to DORM herein will be that described in Section 5. The per cent error in total daily R, P, and P/R caused by using DORM with the graphical procedure assumptions was given along with other formations in Table 7.1. Most of this error is from neglecting surface exchange. This underlines the importance of measuring surface exchange in the stream reach to be studied. The potential errors in estimating surface exchange coefficient from diel D.O. curves or from literature equations are simply too great when one considers the significance of surface exchange in diel curve analysis. It is also noteworthy that the effects of errors on the P/R ratio in Table 7.1 are much less than on P and R individually.

Diel curve analysis was performed with DORM on the diel D.O. measurements described in Section 4. The following parameter values were used:

$\theta = 1.045$ (for respiratory temperature dependence)
NOR = 3 (for interpolation of upstream D.O. measurements)
$D^* = 0.01$ (for longitudinal dispersion)
$C_{KM} = 0.0$ for 6-9 reaches in 1979 surveys
$C_{KM} = 2.3\ \mathrm{g/m^3}$ for 10-13 reaches in 1979 surveys (for respiratory inhibition at low D.O. concentration)
$C_{KM} = 0.0$ for 1978 surveys

and for D.O. surface exchange Eq. 6-3

$$A_1 = 5.44\mathrm{x}10^{-4}$$

$$A_5 = 0.46, \text{ and } A_7 = 4.2\mathrm{x}10^{-5}\ (\mathrm{m/sec})^{-5} .$$

The low D* value is used because the numerical diffusion coefficient given by Eq. 6-17 for the computations is approximately equal to the physical dispersion coefficient of the MERS field channels as measured by Stefan et al (1980). Weather data input and the computational results for all data sets are given in Gulliver and Stefan (1981a). Use of the above parameter values is herein called the "complete DORM" procedure for diel curve productivity analysis.

The graphical and numerical estimates for P, R, and P/R are summarized in Table 8.1. The first column gives the results when the complete DORM is used. The second column presents the results obtained with computer routing when the assumptions inherent in the graphical procedure are used in DORM ($\theta = 1.0$, $D_L = 0$, $C_{KM} = 0$, $K_2 = 0$, NOR = 1). The third column gives the results obtained by direct application of the graphical procedure (Mattke and Stefan, 1980) without the aid of a computer.

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TABLE 8.1. TOTAL DAILY P & R VALUES OBTAINED BY THE NUMERICAL MODEL (DORM) AND THE GRAPHICAL PROCEDURE

			Total Daily R (g/m^2)			Total Daily P (g/m^2)			P/R Ratio		
Date	Channel	Segment	Complete DORM	Graphical DORM	Graphical without DORM	Complete DORM	Graphical DORM	Graphical without DORM	Complete DORM	Graphical DORM	Graphical without DORM
9-05-78	7	11 → 15	6.11	4.80	5.02	3.54	3.14	3.24	.58	.65	.65
9-11-78	7	12 → 17	6.56	5.30	6.02	3.71	3.18	3.54	.57	.60	.59
9-13-78			5.31	4.18	—	*1.50	*1.35	—	* .28	* .32	--
9-20-78	7	12 → 17	4.38	3.43	3.76	2.40	1.86	2.03	.48	.53	.54
9-29-78	7	12 → 17	4.37	3.43	3.54	2.14	1.83	2.23	.49	.53	.63
10-8-78	7	9 → 15	2.64	2.08	2.49	1.50	1.32	2.10	.57	.64	.84
5-30-79	6	6 → 11	3.12	2.39	2.34	5.04	4.14	4.21	1.62	1.73	1.80
	7	6 → 11	3.59	2.67	2.19	6.21	5.08	4.92	1.73	1.90	2.25
	8	6 → 11	2.84	1.84	2.42	4.98	3.80	4.38	1.75	2.07	1.81
	8	8 → 11	3.07	2.27	—	4.93	3.81	—	1.60	1.68	--
	8	6 → 7	3.35	2.78	—	6.06	5.44	—	1.81	1.96	--
5-15-79	6	6 → 9	3.33	2.59	2.76	5.33	4.56	4.82	1.60	1.76	1.75
	7	6 → 9	3.97	3.08	3.16	8.17	7.09	7.56	2.06	2.30	2.39
	8	6 → 9	3.42	2.57	2.74	5.56	4.70	5.02	1.62	1.83	1.83
5-24-79	6	6 → 9	4.06	3.14	3.28	5.27	4.58	4.83	1.30	1.46	1.47
	7	6 → 9	6.10	4.92	5.27	11.32	11.11	10.95	1.86	2.05	2.08
	8	6 → 9	4.77	3.69	3.68	8.89	7.88	8.19	1.86	2.14	2.23
6-06-79	6	6 → 9	4.18	3.60	3.72	5.26	4.80	4.93	1.26	1.33	1.33
	7	6 → 9	8.56	7.42	--	12.49	11.30	—	1.46	1.52	--
	8	6 → 9	6.82	5.86	5.63	11.50	10.27	7.32	1.68	1.75	1.30
6-27-79	6	6 → 9	8.01	6.58	6.70	14.79	13.39	13.94	1.85	2.03	2.08
	7	6 → 9	7.11	5.82	5.00	7.26	6.38	5.92	1.02	1.10	1.18
	8	6 → 9	7.45	6.34	5.87	9.37	8.54	8.13	1.26	1.35	1.39
7-31-79	6	6 → 9	8.07	6.88	7.34	11.91	11.00	11.55	1.48	1.60	1.57
		10 → 13	9.93	6.80	8.01	10.08	6.99	7.75	1.02	1.03	0.97
	7	6 → 9	8.41	7.34	8.69	5.11	4.66	5.24	.61	.64	0.60
	8	6 → 9	7.47	6.38	7.74	4.47	4.08	4.94	.60	.64	0.64
8-1-79	6	6 → 9	8.22	6.88	7.70	13.32	12.23	13.23	1.63	1.78	1.72
		10 → 13	10.69	6.80	9.41	10.46	6.27	8.10	.98	.92	0.86
	7	6 → 9	8.49	7.34	9.28	5.86	5.11	6.31	.69	.70	0.68
	8		7.55	6.38	8.29	4.74	4.08	5.24	.63	.64	0.63
9-18-79	6	6 → 9	6.08	5.32	5.96	6.43	5.99	6.44	1.06	1.13	1.08
	7	6 → 9	6.07	5.40	6.12	5.75	5.35	5.98	.95	.99	0.98
	8	6 → 9	5.32	4.69	5.55	4.74	4.40	4.99	.89	.94	0.90

*Suspect D.O. data during daylight hours.

The complete DORM gave generally higher values of R and P because of the omission of surface exchange in the graphical procedure. There are also differences between the graphical procedure with and without DORM because each used a different criterion for choosing a representative community respiratory rate from night D.O. measurements.

The graphical procedure simulated with DORM used an average R from night D.O. measurements. In the true graphical procedure (without DORM) the R value determined from D.O. measurements early in the evening was used. Since respiratory rate is dependent upon temperature and D.O. concentration, these two R values were often different. This indicates that the criterion used for choosing a representative community respiratory rate from night D.O. measurements is also important in diel curve productivity analysis.

Table 8.2 summarizes the ratios of R values and P values from Table 8.1 obtained by the complete DORM and the graphical method on DORM. The graphical method gave R and P values which were consistently (throughout the season) 82 and 89 per cent, respectively, of the best estimate obtained through the use of the complete DORM. These comparisons are only applicable to the MERS experimental channels. The ratios for other streams could be higher or lower, depending on the relative contribution of surface exchange.

SEASONAL COMMUNITY RESPIRATION RATES AND COMMUNITY PHOTOSYNTHETIC RATES

The estimates of total daily photosynthetic production and respiration uptake by the complete DORM procedure are given in Table 8.3. In addition, the computed value of R_{20} which may be interpreted as a measure of total community biomass, is listed. The seasonal variation of R_{20} for each channel plotted in Fig. 8.1 shows highly dynamic changes in May and June and a slow steady decline in July, August, and September. These R_{20} values include both plant and bacterial respiration so that the slow seasonal decline does not necessarily mean that living plant biomass is constant, since bacterial decomposition of dead plant biomass is also included in R_{20}. Field measurements of sediment oxygen demand (SOD) described by Mattke and Stefan (1980) indicated that SOD was less than 0.1 g m^{-2} hr^{-1}. The maximum observed 5-day BOD based on a water sample withdrawn from the channel was 12 mg/ℓ (K.E.F. Hokanson, personal communication, MERS, USEPA). Therefore, community respiration associated with particulate organic matter and plankton in water samples was

TABLE 8.2. TOTAL DAILY PHOTOSYNTHESIS (P) AND RESPIRATION (R) COMPUTED BY DORM SIMULATING THE GRAPHICAL PROCEDURE AND BY THE COMPLETE DORM PROCEDURE

	R Graph / R Complete	P Graph / P Complete	(P/R) Graph / (P/R) Complete
Upstream			
Channel 6			
Average	0.82	0.89	1.08
St. Dev.	0.04	0.04	0.03
Minimum	0.77	0.82	1.05
Maximum	0.88	0.93	1.12
Channel 7 (1979)			
Average	0.83	0.90	1.06
St. Dev.	0.05	0.05	0.04
Minimum	0.74	0.82	1.01
Maximum	0.89	0.98	1.12
Channel 8			
Average	0.81	0.88	1.08
St. Dev.	0.08	0.05	0.06
Minimum	0.65	0.76	1.02
Maximum	0.88	0.93	1.18
All Channels			
Average	0.82	0.89	1.07
St. Dev.	0.05	0.05	0.04
Minimum	0.65	0.76	1.01
Maximum	0.89	0.98	1.18
Downstream			
Channel 7 (1978)			
Average	0.79	0.82	1.10
St. Dev.	0.01	0.05	0.03
Minimum	0.78	0.90	1.05
Maximum	0.81	0.78	1.14

TABLE 8.3. TOTAL DAILY ESTIMATES OF COMMUNITY PHOTOSYNTHESIS AND RESPIRATION WITH DORM FOR THE MERS FIELD CHANNELS

Channel	Reach	Date	Total Daily Respiration	Total Daily Photosynthesis	P/R	R_{20}	Daily PAR	$\frac{P}{R \cdot PAR}$	$\frac{P}{PAR}$	Mean Water Temperature	pH
			g/m^2	g/m^2		$g/m^2/hr$	E/m^2	m^2/E	g/E	°C	Pool 6
7	11-15	9-05-78	6.11	3.54	.58	.233	41.0	.0141	.086	22.9	
	12-17	9-11-78	6.56	3.71	.57	.235	35.0	.0162	.106	24.3	
		9-13-78	5.31	1.49	.28	.244	6.3	.0444	.236	18.2	
		9-20-78	4.38	2.10	.48	.222	18.5	.0259	.114	15.6	
		9-29-78	4.37	2.14	.49	.228	20.5	.0239	.104	14.8	
		10-08-78	2.64	1.50	.57	.167	31.4	.0181	.048	10.4	
6	6-11	5-03-79	3.12	5.04	1.62	.216	51.6	.0313	.098	9.2	8.1
	6-9	5-15-79	3.33	5.33	1.60	.207	59.1	.0271	.090	11.3	8.1
		5-24-79	4.06	5.27	1.30	.212	60.1	.0216	.088	15.5	8.1
		6-06-79	4.18	5.26	1.26	.180	43.8	.0287	.120	19.6	8.2
		6-27-79	8.02	14.80	1.84	.324	63.5	.0291	.233	22.2	8.1
		7-31-79	8.06	11.91	1.48	.292	30.7	.0481	.388	23.3	8.0
		8-01-79	8.22	13.43	1.63	.292	48.2	.0339	.279	23.7	8.2
		9-18-79	6.08	6.43	1.06	.281	38.0	.0278	.169	17.8	8.3
6	10-13	7-31-79	9.93	10.08	1.01	.482	30.7	.0331	.328	23.2	
		8-01-79	10.69	10.46	.98	.482	48.2	.0203	.217	23.8	
7	6-11	5-03-79	3.59	6.21	1.73	.249	51.6	.0335	.120	9.2	8.1
	6-9	5-15-79	3.97	8.17	2.06	.244	59.1	.0348	.138	11.8	6.0
		5-24-79	6.10	11.32	1.86	.316	60.1	.0309	.188	15.9	6.2
		6-06-79	8.56	12.49	1.45	.369	43.8	.0333	.285	19.5	6.3
		6-27-79	7.11	7.26	1.02	.288	63.5	.0161	.1143	20.7	6.0
		7-31-79	8.41	5.11	.61	.304	30.7	.0199	.166	22.2	6.2
		8-01-79	8.49	5.86	.69	.304	48.2	.0143	.122	23.3	6.2
		9-18-79	6.07	5.75	.95	.281	38.0	.0249	.151	17.8	8.2
8	6-11	5-03-79	2.84	4.98	1.75	.197	51.6	.0340	.097	9.2	8.1
	6-9	5-15-79	3.42	5.56	1.62	.210	59.1	.0275	.094	12.1	5.1
		5-24-79	4.77	8.89	1.86	.248	60.1	.0310	.148	15.7	5.2
		6-06-79	6.82	11.50	1.68	.293	43.8	.0385	.263	19.5	5.4
		6-27-79	7.45	9.37	1.26	.302	63.5	.0198	.148	20.9	4.9
		7-31-79	7.47	4.47	.60	.270	30.7	.0195	.146	23.2	4.9
		8-01-79	7.55	4.74	.63	.270	48.2	.0130	.098	23.7	5.0
		9-18-79	5.32	4.74	.89	.246	38.0	.0234	.125	17.8	8.1

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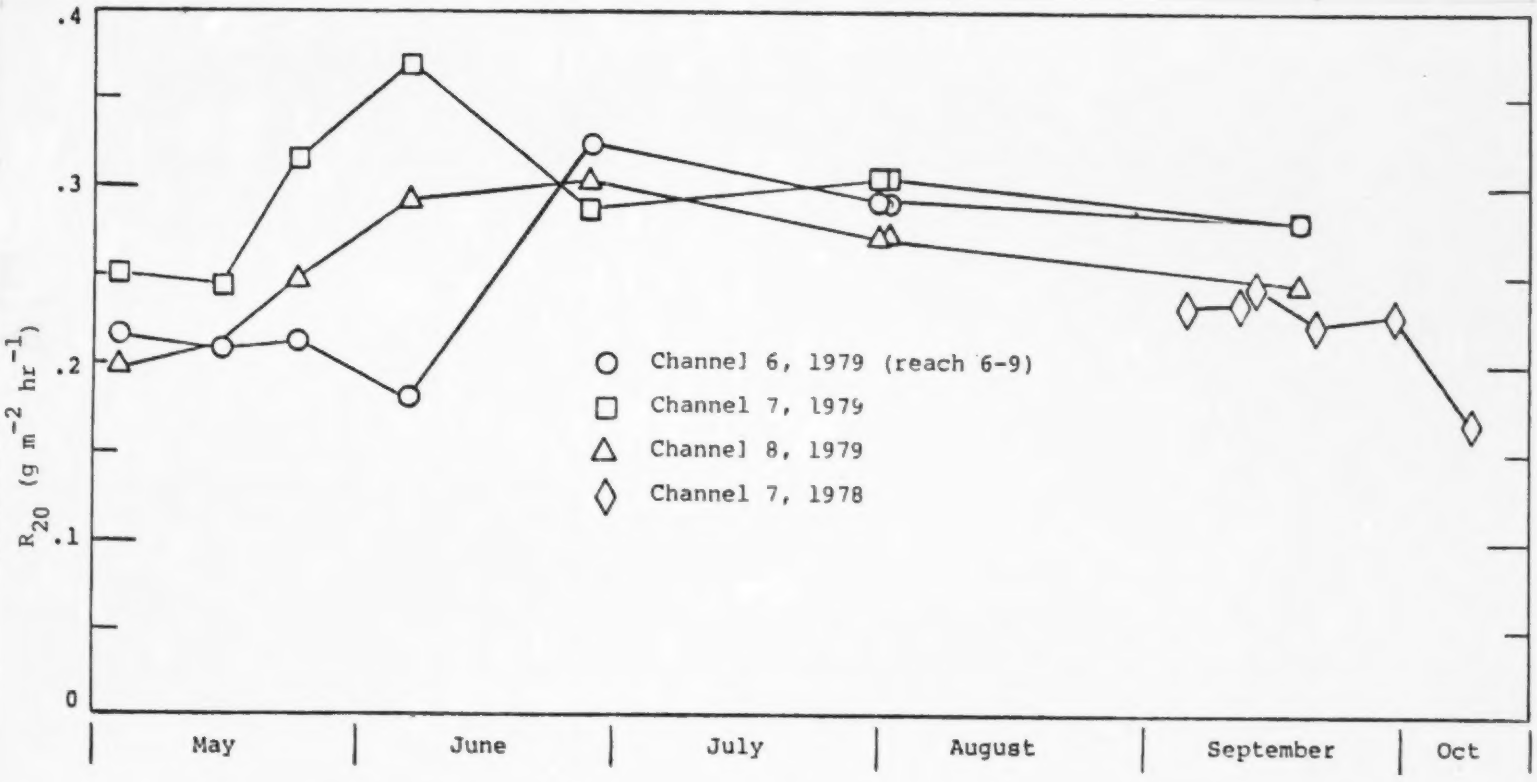

Fig. 8.1. R_{20} values from DORM diel curve analysis of the MERS field channels.

less than $R = 0.1$ mg ℓ^{-1} hr^{-1} or $R = 0.04$ g m^{-2} hr^{-1} in the MERS channels. The peaks in R_{20} are likely to be artificially tempered because the operation of the channels by the MERS staff required periodic raking in the riffle sections when plant biomass was excessive. Visual observations were used to estimate that approximately 10 per cent of the channel biomass was removed by every raking.

Figure 8.1 does indicate that the development of the autotrophic community occurred at different rates in each channel. The most likely reason for this difference between channels is that channels 7 and 8 were "older" since they had water in them for five years previous to the summer of 1979, compared to two years for channel 6.

In situ, measurements described by Taylor and Sheldon (1980) and summarized in Appendix E indicated that the planktonic contribution to community photosynthesis and respiration was less than 1 g m^{-2} day^{-1}. Photosynthesis and respiration was predominantly from the macrophytic and epiphytic communities in pools and from the benthic community in riffle sections. The macrophytic community will be more firmly established in the older channels, and an equilibrium biomass ($P/R = 1$) will develop earlier in the growing season. There was also a difference in pH between the channels. An increase in photosynthetic production when pH is reduced from 7 or 8 to 5 or 6 is well documented (Best and Meulemans, 1978). This would give a higher photosynthetic production in channels 7 and 8 with lower pH. A low pH may also favor species which develop rapidly, accounting for the early season differences between channels.

There were also differences in seasonal patterns of vegetation type between channel 6 and channels 7 and 8. Early in the 1979 growing season the pool vegetation in all three channels was predominantly submerged macrophytes, although much less dense in channel 6. During July and August, however, large portions of the pools in channels 7 and 8 were covered with duckweek (*Lemna sp.*) while the macrophyte population increased in channel 6. Either channel age or pH could account for the difference in seasonal vegetation pattern.

Also given in Table 8.3 are three parameters which may indicate the relative energy utilization of the autotrophic community:

$$P/R = \frac{\text{total daily photosynthetic production}}{\text{total daily respiration}}$$

$$\frac{P}{R\cdot PAR}\ (E/m^2)^{-1} = \text{P/R indexed by daily photosynthetically active radiation, and}$$

$$\frac{P}{PAR}\ (g/E) = \frac{\text{total daily photosynthetic production}}{\text{total daily photosynthetically active radiation}}$$

P/R is often used as an indicator of the degree of autotrophy or heterotrophy in a community. This ratio is obviously dependent upon incoming solar radiation, which can vary from day to day. Figure 8.2 gives P/R ratio for channels 6, 7, and 8 through the 1979 season. Channel 6 shows a remarkably high P/R ratio through most of the season. The P/R ratios for channels 7 and 8 are more typical for streams with a predominantly attached autotrophic community. The decay in photosynthetic efficiency over the season is typical of macrophyte populations, where net photosynthetic potential declines with leaf age (Barko et al, 1977).

Since the P/R ratio is obviously dependent upon incoming light, the P/(R•PAR) ratio was thought to index the P/R ratio to light intensity. Figure 8.3 gives the seasonal trends of P/(R•PAR) in channels 6, 7, and 8. It is immediately obvious that there is a greater scatter in the seasonal patterns of P/R•PAR) than in P/R ratios. Days with low light intensity such as July 31 have a larger ratio of P/(R•PAR) than days with a higher PAR such as August 1. Table 8.3 indicates the same occurrence in 1978, where 9/11 and 9/13 P/R.PAR) ratios differ greatly. The P/(R•PAR) ratio does not work well because total daily P is not linearly dependent upon PAR. On days with high light intensity, afternoon photosynthetic rates are significantly reduced, causing a large clockwise hysteresis in the P versus PAR curve. In the MERS channels the P/R ratio is more meaningful than P/(R•PAR).

Simonsen and Harremöes (1978) found that total community photosynthetic rates (or daily gross production) were unrelated to community biomass. The seasonal variation of total daily photosynthetic production (TP) given in Fig. 8.4 may be compared with the P/R ratios in Fig. 8.2 to test this hypothesis. The trends in P/R generally correspond to the trends in TP except during the early season when the autotrophic community is establishing itself. This means that for the MERS field channels photosynthetic production is related to biomass in the early season until the community is fully established. During the later half of the season there is no discernible correlation between photosynthetic production and community biomass.

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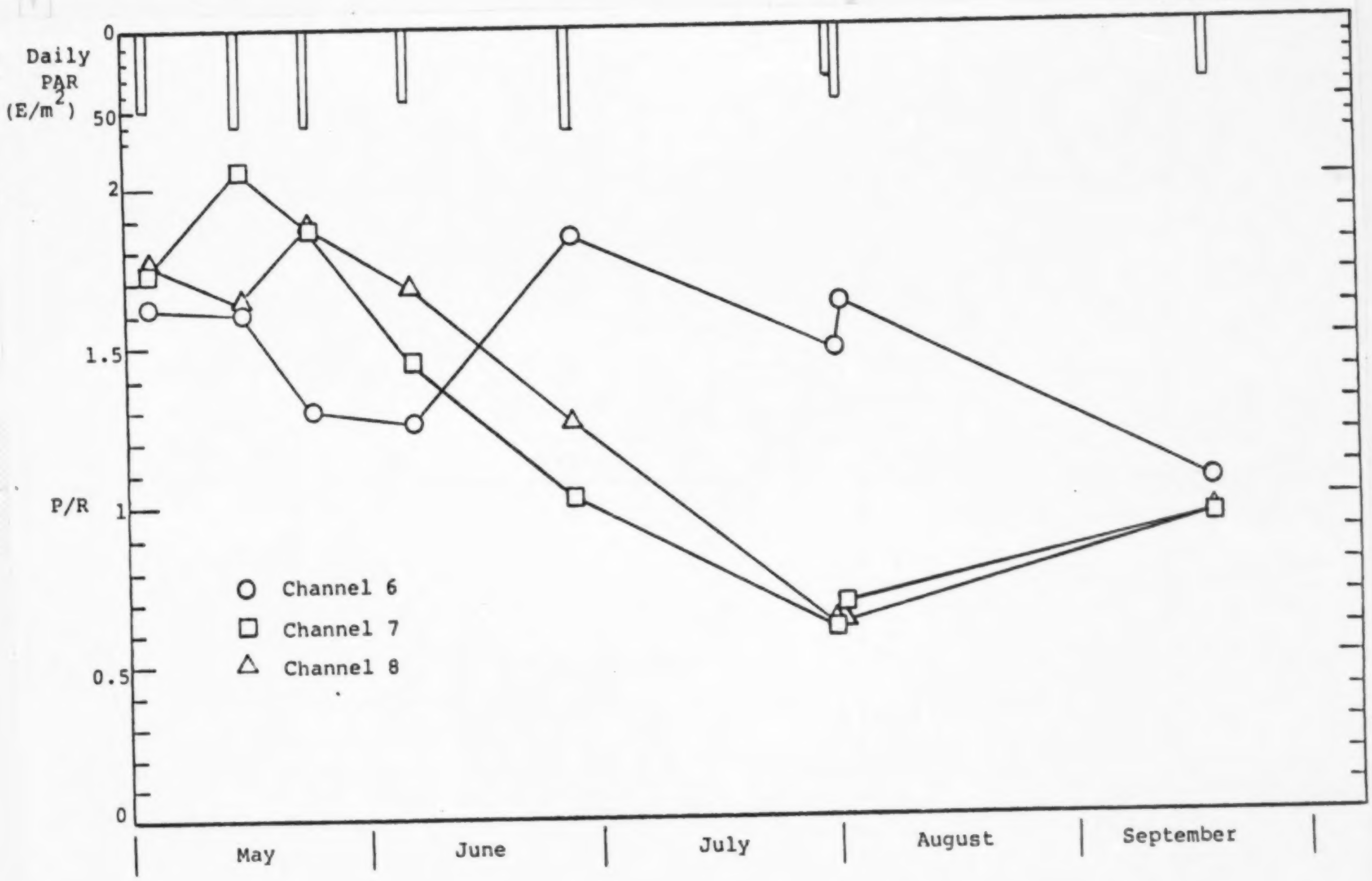

Fig. 8.2. Seasonal variation in P/R ratio from 1979 diel curve analyses.

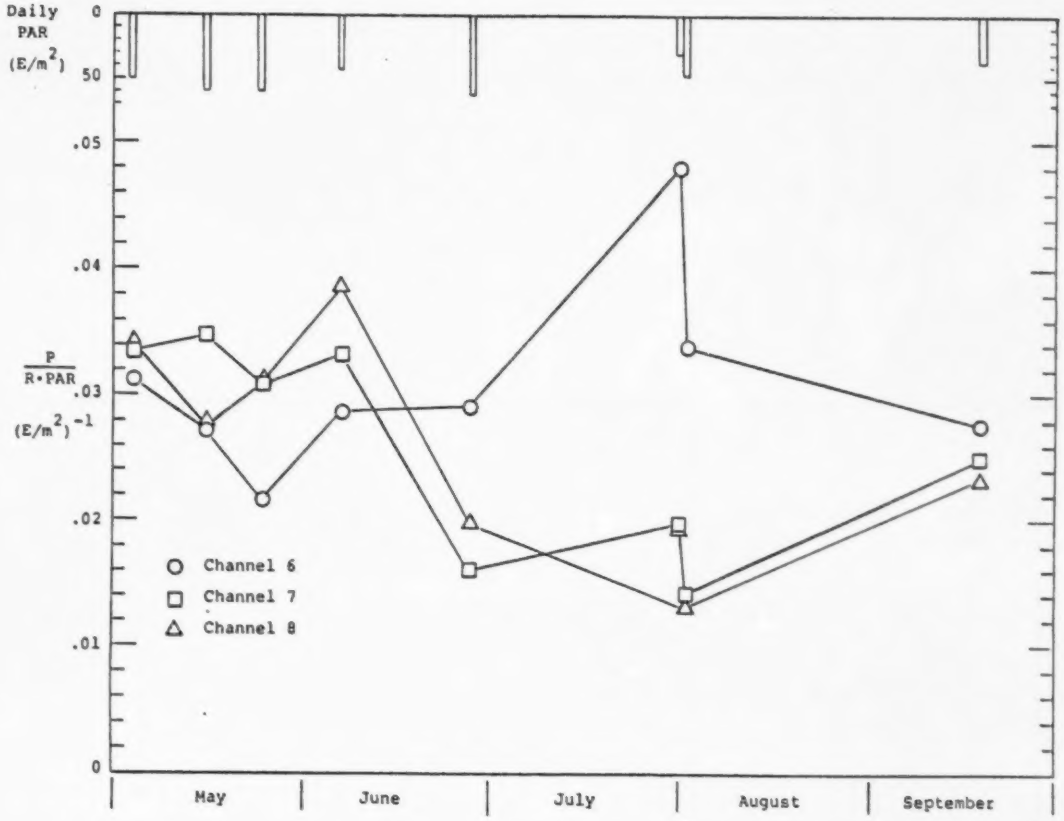

Fig. 8.3. Seasonal variation in P/(R·PAR) from 1979 diel curve analyses.

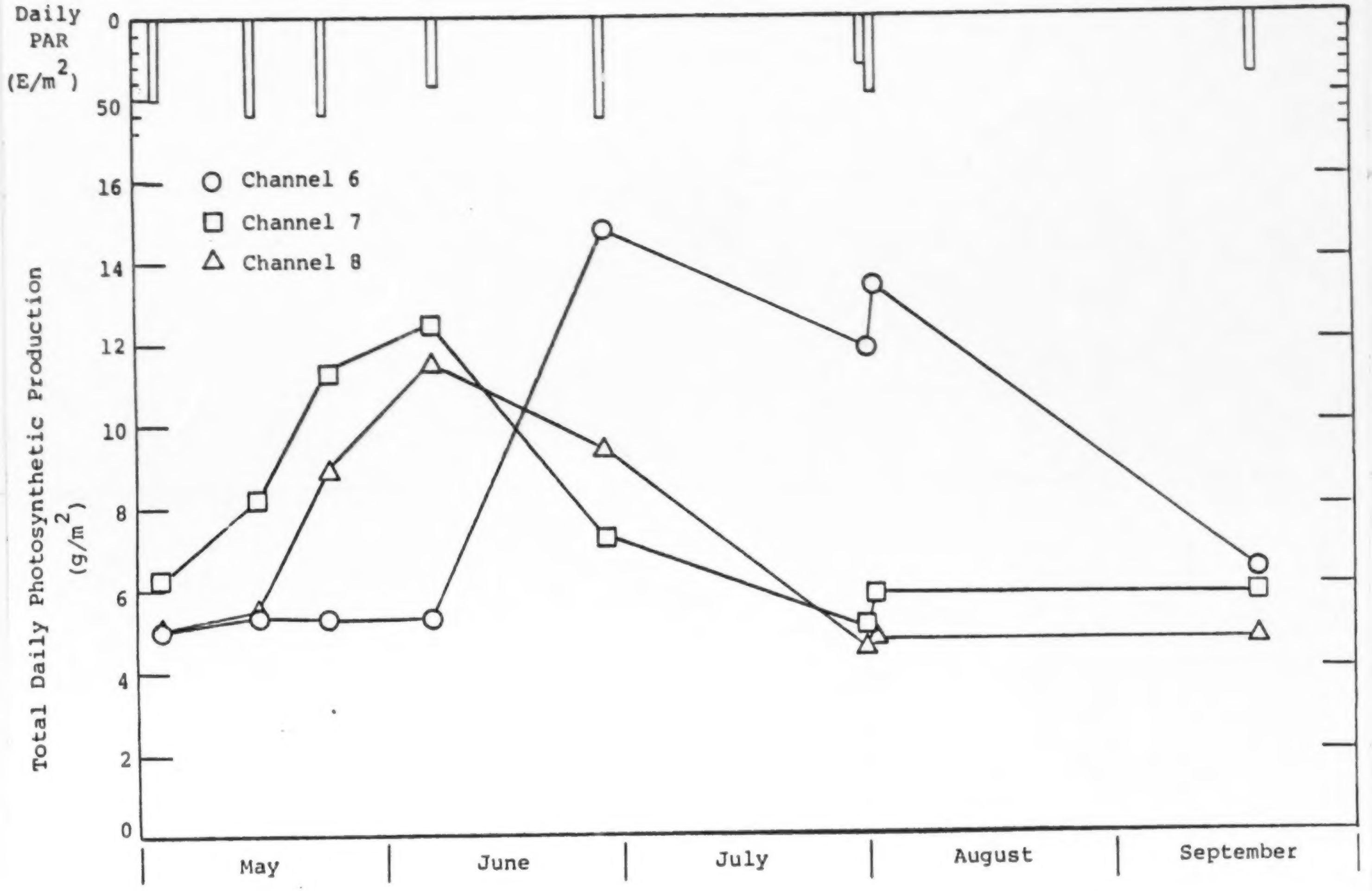

Fig. 8.4. Seasonal variation in total daily photosynthetic production from 1979 diel curve analyses.

DIEL COMMUNITY PHOTOSYNTHESIS RATES

The diel cycle of gross community photosynthetic oxygen production rates by the community may be related to daily light cycles. Photosynthetic rates computed from diel curve analysis were plotted against PAR for each of the diel D.O. surveys. The resulting P versus PAR curves are given in Gulliver and Stefan (1981a). A sample is given in Fig. 8.5. The numbers near each point give measured downstream D.O. concentrations and the arrows reflect the order of sample estimates throughout the day. A maximum P is often approached at high light intensities which could indicate light saturation. A lower P is frequently observed for the same PAR later in the day. This deviation from an expected linear relationship is called hysteresis of the P versus PAR relationship. The example in Fig. 8.5 illustrates clockwise hysteresis which is predominant in the result of the diel curve analyses. At first glance there does not appear to be any coherent pattern in the P versus PAR hysteresis, which can be clockwise or counter-clockwise and can be non-existent or very large.

There are many factors and processes which influence P and R and which may also cause hysteresis of P versus PAR curves determined by diel curve analysis. Physical and biological phenomena can cause hysteresis. Unfortunately, additional experimental verification of this phenomenon is needed. Counter-clockwise hysteresis in a P versus PAR curve may be caused by:

1. Using a hydraulic residence time for the channel reach which is much too small. Previously in Section 7 an error of 20 per cent in residence time was shown to cause a small counter-clockwise hysteresis.

2. Using a surface exchange coefficient which is too large in diel curve analysis. Figures 7.11 and 7.13 indicate that for the MERS field channels this can account for only a small counter-clockwise hysteresis.

3. A lag in the release of dissolved oxygen from the internal lacunae of vascular plants. Hartman and Brown

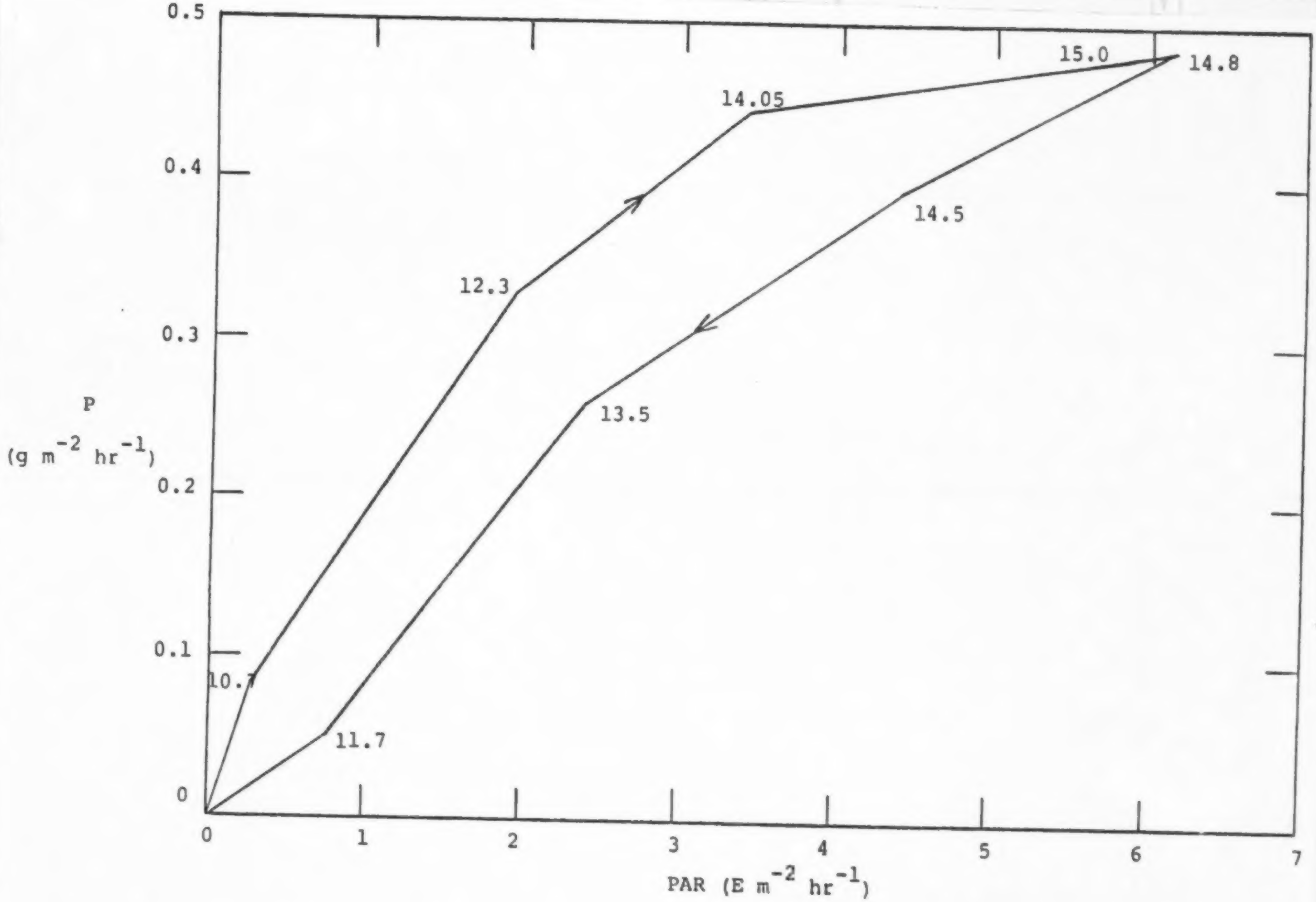

Fig. 8.5. P versus PAR curve for May 3, 1979 diel D.O. survey in channel 6, reach 6-11. Numbers indicate downstream D.O. concentration.

(1967) postulated that oxygen accumulates rapidly in the internal lacunae of vascular plants and slowly diffuses out into the surrounding water. Westlake (1978), however, measured this lag time to be less than 20 minutes for two species of vascular plants. The average lag time was on the order of 9 minutes. Nevertheless, a lag time as small as 1/2 hour can produce hysteresis.

4. Dead zone storage due to stratification or dead zones along the channel reach. The stratification which periodically occurs in the MERS field channels was shown by Hahn et al (1978) to contain approximately 10% of the channel volume. Dead zone storage would have the same effect as using too small a residence time in diel curve analysis, and it would take a very large (20 per cent of the channel volume) dead zone storage to significantly contributed to hysteresis.
5. A large amount of shading on the east bank of the channel and little or no shading on the west bank. This general trend was not observed in the MERS channels.
6. Inhibition of respiration by light, as hypothesized by Hough (1974).
7. Other biological phenomena unknown to the authors.

Clockwise hysteresis in a P versus PAR curve may be caused by:

1. Using a channel reach hydraulic residence time in diel curve analysis which is too large.
2. Using a surface exchange coefficient in diel curve analysis which is too small. This is a potential problem if no surface exchange measurements have been made for the channel reach.

3. Neglecting longitudinal dispersion in a highly dispersive stream. This does not apply to the MERS field channels.

4. A large amount of shading on the west bank of the channel and little or no shading on the east bank. This general trend was not observed in the MERS channels.

5. Nutrient limitation in plant cells (Senft, 1978) which can occur as the day progresses and the use of nutrients exceeds nutrient uptake.

6. Photorespiration, which is the light-induced uptake of oxygen resulting from glycolate metabolism (Hough, 1974; Hough and Wetzel, 1975; Wetzel, 1975). Photorespiration is enhanced by light intensity, D.O. concentration, and water temperature. Hough (1974) found that photorespiration was predominant in one species of submersed vascular plant in the latter half of the day, reducing net photosynthesis.

7. Dissolved oxygen toxicity, which occurs when dissolved oxygen concentration in the cells reaches such a high value that it becomes toxic and limits photosynthesis.

8. Other biological phenomena unknown to the authors.

Table 8.4 is designed to sort out the confusing patterns of hysteresis in the P versus PAR curves, where the extent of hysteresis is judged qualitatively by the size of the hysteresis loop. There are only two days of diel D.O. data for which counter-clockwise hysteresis is predominant. Counter-clockwise hysteresis occurred in all of the P versus PAR curves on July 31, an overcase day with low PAR. By contrast, the next day was clear and all channel reaches had a clockwise hysteresis. Any of the physical reasons given for clockwise hysteresis would apply for both July 31 and August 1. This indicates that the counter-clockwise hysteresis on July 31 is of biological origin, e.g. on the cloudy day the autotrophic community used light more efficiently in the latter half of the day. A lag of 30 minutes in the release of D.O. could not account for the large counter-clockwise hysteresis on July 31 and the day was cloudy so that light-induced inhibition of respiration would seemingly not apply.

The small counter-clockwise hysteresis in channel 7 on May 15 and May 24, 1979 could have been caused by an error in residence time or by dead zone storage.

The large counter-clockwise hysteresis on September 18, 1979, and September 29, 1978, cannot be interpreted easily. It is highly unlikely that errors in diel curve analysis could cause such a large hysteresis. The hysteresis could have been caused by a lag of 20 to 30 minutes in the release of D.O. from the internal lacunae of vascular plants, but if such a lag existed, it should have occurred throughout the season.

Some of the reasons for the clockwise hysteresis which occurs in most of the P versus PAR curves are well documented. Photorespiration, nutrient limitation, and dissolved oxygen toxicity have been shown to account for a large clockwise hysteresis. The clockwise hysteresis in any or all of the MERS field channels could be due to any or all of these phenomena. One explanation for the seasonal inconsistency in the hysteresis is that most or all of the biological phenomena listed above (a lag in the release of D.O., light-induced inhibition of respiration, nutrient limitation, photorespiration, and dissolved oxygen toxicity) contribute to each P versus PAR curve, and any one or more can dominate on a given day depending upon light, D.O. concentration, water temperature, and community age.

Even when the overt errors in diel curve analysis are reduced, interpretation of the results on a daily cycle is difficult. In diel curve analyses of the MERS field channels with DORM the potential errors caused e.g. by neglecting longitudinal dispersion or use of an incorrect residence time or surface exchange coefficient could be determined. This adds credibility to the diel curve analysis results and enables the investigator to isolate phenomena which can only be interpreted as a response of the autotrophic community.

TABLE 8.4. INFORMATION RELEVANT TO THE OCCURRENCE OF HYSTERESIS IN P VERSUS PAR CURVES

Date	Channel	Reach	Total Daily Photo-synthesis	Daily PAR	Maximum D.O. con-centration	Magnitude and Type of Hysteresis	
			g/m^2	E/m^2	(g/m^3)		
9-05-78	7	11-15	3.54	41.0	7.7	Medium	Clockwise
9-11-78		12-17	3.71	35.0	7.8	Large	Clockwise
9-13-78			1.49	6.3	6.9	Medium	Clockwise
9-20-78			2.10	18.5	9.3	Medium	Clockwise
9-29-78			2.14	20.5	9.3	Medium	Counter-Clockwise
10-08-78			1.50	31.4	10.85	Medium	Clockwise
5-03-78	6	6-11	5.04	51.6	15.0	Medium	Clockwise
	7		6.21		15.95	Small	Clockwise
	8		4.98		15.3	Large	Clockwise
5-15-79	6	6-9	5.33	59.1	13.6	None	
	7		8.17		16.3	Small	Counter-Clockwise
	8		5.56		13.8	Small	Clockwise
5-24-79	6		5.27	60.1	11.6	Medium	Clockwise
	7		11.32		16.0	Small	Counter-Clockwise
	8		8.89		14.25	Large	Clockwise
6-06-79	6		5.26	43.8	10.8	Large	Clockwise
	7		12.49		14.2	Medium	Clockwise
	8		11.50		14.85	Large	Clockwise
6-27-79	6		14.80	63.5	16.4	Medium	Clockwise
	7		7.26		10.7	Medium	Clockwise
	8		9.37		11.85	Large	Clockwise
7-31-79	6		11.91	30.7	13.25	Large	Counter-Clockwise
		10-13	10.08		14.75	Medium	Counter-Clockwise
	7	6-9	5.11		9.2	Large	Counter-Clockwise
	8		4.47		8.75	Large	Counter-Clockwise
8-01-79	6		13.43	48.2	15.7	Small	Clockwise
		10-13	10.46		17.15	Very Large	Clockwise
	7	6-9	5.86		10.55	Small	Clockwise
	8		4.74		9.6	Medium	Clockwise
9-18-79	6		6.43	38.0	13.1	Large	Counter-Clockwise
	7		5.75		12.4	Large	Counter-Clockwise
	8		4.74		11.6	None	

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APPENDIX A

DORM Program Listing and Sample Input

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      PROGRAM DORM(INPUT,RESULTS,TAPE8,TAPE9=RESULTS)
C
C        MINNESOTA DISSOLVED OXYGEN ROUTING MODEL
C
C        DEVELOPED FOR:
C             MONTICELLO ECOLOGICAL RESEARCH STATION
C             U. S. ENVIRONMENTAL PROTECTION AGENCY
C
C        BY:
C             SAINT ANTHONY FALLS HYDRAULICS LABORATORY
C             UNIVERSITY OF MINNESOTA
C
C        THIS MODEL NUMERICALLY ROUTES STREAM DIEL DISSOLVED OXYGEN
C        MEASUREMENTS BETWEEN TWO LOCATIONS TO DETERMINE TOTAL
C        COMMUNITY PHOTOSYNTHETIC AND RESPIRATORY RATES
C
C        THE MAIN FEATURES OF THE MODEL ARE:
C
C        1.AN ALGEBRAIC CURVE OF ANY DESIRED ORDER IS FIT THROUGH
C          UPSTREAM D.O. MEASUREMENTS TO GIVE THE BEST CONTINUOUS
C          ESTIMATE OF D.O. CONCENTRATION FLOWING INTO THE CHANNEL
C          REACH,
C        2.WATER SURFACE D.O. EXCHANGE IS INCLUDED,
C        3.THE DEPENDANCE OF TOTAL COMMUNITY RESPIRATORY RATE ON WATER
C          TEMPERATURE AND D.O. CONCENTRATION IS INCORPORATED, AND
C        4.LONGITUDINAL DISPERSION MAY BE MODELLED.
C
C
C        THE PROGRAM IS WRITTEN IN MINNESOTA FORTRAN
C        WHICH IS SIMILAR TO WATFOR
C        NON-STANDARD CONVENTIONS USED ARE:
C          1. 7-CHARACTER NAMES,
C          2. NON-STANDARD SUBSCRIPTS AND DO LOOP INDICES,AND
C          3. NON-STANDARD FORMAT.
C
C
C        LIST OF INPUT VARIABLES:
C
C        ACS(K) = MEAN CROSS-SECTIONAL AREA OF CHANNEL SEGMENT(FT*FT)
C        CHANNEL = ALPHANUMERIC IDENTIFIER OF CHANNEL REACH
C        CHDIR(K) = DIRECTION OF CHANNEL CENTERLINE AT SEGMENT K (DEG)
C        CI(K) = INITIAL D.O. CONCENTRATION AT THE UPSTREAM END OF CHANNEL
C              SEGMENT K (G/M**3/HR)
C        CKM = CONSTANT FOR DEPENDENCE OF RESPIRATORY RATE ON D.O. CONCENTRA
C        CK1,CK2,CK3, = COEFFICIENTS FOR REAERATION EQUATION
C        CT(1,J) = JTH UPSTREAM MEASURED D.O. CONCENTRATION (G/M**3)
C        CT(2,J) = JTH DOWNSTREAM MEASURED D.O. CONCENTRATION (G/M**3)
C        DATE = MONTH DAY OF STARTING DAY
C        DAY = JULIAN DAY OF YEAR FOR STARTING DAY
C        DELX = COMPUTATIONAL DISTANCE INCREMENT (FT)
C        DLAT = LATITUDE OF SITE (DEGREES)
C        DLONG = LONGITUDE OF SITE (DEGREES)
C        DMERID = LONGITUDE OF TIME ZONE MERIDIAN (DEGREES) (FOR COMPUTING
C                 ACCURATE SUNRISE AND SUNSET TIMES)
C        DSTAR = DIMENSIONLESS LONGITUDINAL DISPERSION COEFFICIENT
C              = DL*WIDTH/FLOW
C        DTIME = COMPUTATIONAL TIME INCREMENT (SEC)
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00058C        EPS = COEFFICIENT FOR FORMULATION OF FINITE DIFFERENCES
00059C              = 1.0 FOR FULLY IMPLICIT
00060C              = 0.5 FOR CRANK-NICOLSON IMPLICIT
00061C              = 0.0 FOR EXPLICIT
00062C        ERRMAX = MAXIMUM ALLOWABLE DIFFERENCE IN PHOTOSYNTHETIC OR
00063C                 RESPIRATORY RATES BETWEEN SUCCESSIVE ITERATIONS
00064C        FLOW = AVERAGE FLOW RATE FOR TOTAL PERIOD OF D.O. ROUTING (GPM)
00065C        IDSEG(K) = INTEGER IDENTIFICATION OF CHANNEL SEGMENT K
00066C        IT,IH,AND IY = HEADINGS FOR PLOT OF D.O. MEASUREMENTS
00067C        ITERMAX = MAXIMUM NUMBER OF ITERATIONS IN RESPIRATION AND
00068C                  PHOTOSYNTHESIS CALCULATIONS
00069C        NDATA = NUMBER OF DOWNSTREAM D.O. MEASUREMENTS
00070C        NDAYS = NUMBER OF DAYS IN D.O. ROUTING
00071C              = NUMBER OF DAYLIGHT PERIODS DURING D.O. MEASUREMENTS
00072C        NFLAG = 1 IF FITTED UPSTREAM D.O. CONC. AND PLOT OF MEASURED
00073C                D.O. CONC. ARE TO BE OUTPUT
00074C        NITER = MAXIMUM NUMBER OF ITERATIONS ON SURFACE EXCHANGE ROUTINE
00075C                AT A GIVEN TIME STEP
00076C        NOR = ORDER OF ALGEBRAIC EQUATION TO BE FIT THROUGH UPSTREAM
00077C              D.O. MEASUREMENTS
00078C        NSEG = NUMBER OF SEGMENTS IN CHANNEL REACH
00079C        NUDATA = NUMBER OF UPSTREAM D.O. MEASUREMENTS
00080C        PHOLAG = LAG IN PLANT RELEASE OF PHOTOSYNTHETICLY PRODUCED
00081C                 OXYGEN (HR)
00082C        PRESSUR = AVERAGE AIR PRESSURE FOR TOTAL PERIOD OF D.O. ROUTING (MM
00083C        RM = INITIAL (FIRST GUESS) STANDARD RESPIRATORY RATE AT 20 DEG. C.
00084C             (G/(M*M*HR))
00085C        RUNTIME = TOTAL TIME OF COMPUTER RUN (HR)
00086C        SLENGTH(K) = LENGTH OF CHANNEL SEGMENT K (FT)
00087C        T(K,J) = WATER TEMPERATURE AN CHANNEL SEGMENT K AND TIME STEP J (DEC
00088C                 MUST BE KNOWN AT TWO SEGMENTS FOR EACH TIME STEP. VALUES II
00089C                 AS 0.0 ARE ESTIMATED BY PIECE-WISE LINEAR APPROXIMATION.
00090C        THETA = ARRHENIUS CONSTANT FOR TEMPERATURE DEPENDENCE OF RESPIRATORY
00091C                RATE
00092C        TLENGTH = TOTAL LENGTH OF CHANNEL REACH (FT)
00093C        TMEAS (1,J) = MEASUREMENT TIME FOR JTH UPSTREAM MEASURED D.O.
00094C                      CONCENTERTION (HOUR.MINUTE). 1:00 AM ON SECOND DAY = :
00095C        TMEAS(2,J) = MEASUREMENT TIME FOR JTH DOWNSTREAM MEASURED
00096C                     D.O. CONCENTRATION
00097C        TSTART = STARTING TIME (HOUR OF DAY)
00098C        TWEATHR = TIME BETWEEN INPUT OF WEATHER DATA (HR)
00099C        W(J) = WIND VELOCITY AT TIME STEP J (M/SEC)
00100C        WDIR(J) = WIND DIRECTION AT TIME STEP J (DEGREES)
00101       COMMON/A/ C(80,2),CO(500),CT(2,35),TMEAS(2,35),CIE(80),NOR
00102       COMMON/B/ FC(80),PE(80),S(80),H(80),A(80),DL(80),FK(17,35)
00103       COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,BBAR,DSTAR,CKM,THETA,DBAR

00104       COMMON/D/ P(35),RESID(35),R(35),TR(35)
00105       COMMON/E/ T(17,35),SE(17,35),RK(17,35),CS(17,35),NSEG,IDSEG(17)
00106      $,ISEG(17),SLENGTH(17),CHDIR(17)
00107       COMMON/F/ F(80),G(80),EPS,FEPS
00108       COMMON/G/ D(35),PA(35),W(35),WDIR(35),CK1,CK2,CK3,SLOPE(17)
00109       COMMON/H/ NDATA,ITERMAX,ERRMAX,TSTART,RUNTIME,ENDTIME,NDAYS
00110       COMMON/I/ IT(6),IH(6),IY(6)
00111       DIMENSION ACS(20),WIDTH(20),CI(17)
00112       EXTERNAL CINFLOW,TEMP,RESPIRE,PHOSYN,RESTIME,CPLOT
00113       INTEGER CHANNEL,DATE,YEAR
00114C
00115C         READ INPUT PARAMETERS
00116C
00117       READ(8,800) DAY,DSTAR,DTIME,DELX,TLENGTH,RM,RUNTIME,
00118      $TWEATHR,TSTART,DLAT,DLONG,DMERID,ERRMAX,EPS,
00119      $PHOLAG,THETA,CKM,FLOW,PRESSUR
00120       READ(8,805)CK1,CK2,CK3
00121       READ(8,810) NSEG,NUDATA,NDATA,ITERMAX,IDSEG(1),NDAYS,NOR,NFLAG
00122C
00123C         READ CHANNEL CHARACTERISTICS
00124C
00125       READ(8,820) (ACS(K),K=1,NSEG+1)
00126       READ(8,820) (WIDTH(K),K=1,NSEG+1)
00127       READ(8,820)(CHDIR(K),K=1,NSEG+1)
00128       READ(8,820) (SLENGTH(K),K=1,NSEG+1)
00129       READ(8,822)(SLOPE(K),K=1,NSEG)
00130       READ(8,825) CHANNEL,DATE,YEAR
00131       READ(8,825) IT,IH,IY
00132C
00133C         CONVERT TO RADIANS AND METRIC UNITS
00134C
00135       DLAT=DLAT*3.14/180.
00136       DLONG=DLONG*3.14/180.
00137       DMERID=DMERID*3.14/180.
00138       DELX=DELX*0.3048
00139       TLENGTH=TLENGTH*0.3048
00140       DO 3 K=1,NSEG+1
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      ACS(K)=ACS(K)*0,3048*0.3048
      WIDTH(K)=WIDTH(K)*0.3048
  3   SLENGTH(K)=SLENGTH(K)*0.3048
C
C        READ INITIAL D.O. PROFILE
C
      READ(8,815) (CI(K),K=1,NSEG+1)
C
C        SET UP PARAMETERS INTERNAL TO THE PROGRAM
C
      ENDTIME=RUNTIME+TSTART
      NWEATHR=RUNTIME/TWEATHR+0,99
      FEPS=(1.-EPS)/EPS
      JWEATHR=TWEATHR+0,01
      JTIME=3600./DTIME+0.01
      IX=TLENGTH/DELX+2,01
      I=1
      SUM=0.0
      SUMB=0.0
      A(1)=ACS(1)
      B(1)=WIDTH(1)
C
C        ASSIGN SEGMENT IDENTIFICATION AND COMPUTE CHANNEL
C        FROM INPUT DATA                         CHARACTERISTICS
C
      DO 10 K=1,NSEG
      IDSEG(K)=IDSEG(1)+K-1
      ISEG(K)=SLENGTH(K)/DELX+0.01
      IF(K.EQ.1.OR.K.EQ.NSEG) ISEG(K)=ISEG(K)+1
      DO 5 L=I,I+ISEG(K)-1
      A(L)=ACS(K)
      SUM=SUM+A(L)
      B(L)=WIDTH(K)
    5 SUMB=SUMB+B(L)
      I=I+ISEG(K)
   10 CONTINUE
      IDSEG(NSEG+1)=IDSEG(1)+NSEG
      A(IX+1)=ACS(NSEG+1)
      BBAR=SUMB/FLOAT(I)
      DBAR=SUM/SUMB
      DO 12 I=1,IX-1
      B(I)=(B(I)+B(I+1))/2.
   12 A(I)=(A(I)+A(I+1))/2.
C
C        SET UP INITIAL D.O. CONC. AT EACH DISTANCE INCREMENT
C
      K=1
      IK=0
      DO 15 I=1,IX
      IK=IK+1
      IF(IK.LE.ISEG(K)) GO TO 13
      K=K+1
      IK=0
  13  CONTINUE
      RC=FLOAT(IK-1)/FLOAT(ISEG(K))
      CIE(I)=(1.-RC)*CI(K)+RC*CI(K+1)
  15  CONTINUE
      CIE(IX+1)=2.*CIE(IX)-CIE(IX-1)
C
C        READ WATER TEMPERATURES AND ASSIGN FLOW AND AIR PRESSURE TO
C        EACH TIME STEP
C
      DO 20 J=1,NWEATHR+1
      Q(J)=FLOW/449.*.3048**3
      PA(J)=PRESSUR*1013./760.
      READ(8,820)(T(K,J),K=1,NSEG+1)
  20  CONTINUE
C
C        READ WIND VELOCITY AND DIRECTION
C
      READ(8,830)(W(J),J=1,NWEATHR)
      READ(8,835)(WDIR(J),J=1,NWEATHR)
C
C        READ D.O. MEASUREMENTS
C
      READ(8,830) (CT(1,J),J=1,NUDATA)
      READ(8,830) (TMEAS(1,J),J=1,NUDATA)
      READ(8,830) (CT(2,J),J=1,NDATA)
      READ(8,830) (TMEAS(2,J),J=1,NDATA)
C
C        ADJUST MEASUREMENT TIMES FROM HOURS.MINUTES TO HOURS.FRACTION AND
C        CHANGE FROM DAYLIGHT SAVINGS TO CENTRAL STANDARD TIME.
C
```

```
      DO 25 J=1,NUDATA
      TMEAS(1,J)=TMEAS(1,J)-1.
   25 TMEAS(1,J)=FLOAT(IFIX(TMEAS(1,J)))+(TMEAS(1,J)
     $-FLOAT(IFIX(TMEAS(1,J))))/0.6
      DO 26 J=1,NDATA
      TMEAS 2,J)=TMEAS(2,J)-1.
   26 TMEAS(2,J)=FLOAT(IFIX(TMEAS(2,J)))+(TMEAS(2,J)
     $-FLOAT(IFIX(TMEAS(2,J))))/0.6
      TMEAS(2,NDATA+1)=0.0
C
C          OUTPUT SELECTED CHANNEL CHARACTERISTICS
C

      WRITE(9,901) CHANNEL
      WRITE(9,900) DATE,YEAR
      WRITE(9,905)
      WRITE(9,907) DTIME,DELX,EPS,DSTAR,ERRMAX,ITERMAX,THETA,CKM,NOR
      WRITE(9,910) (IDSEG(K),K=1,NSEG+1)
      WRITE(9,915) (CI(K),K=1,NSEG+1)
      WRITE(9,920) (SLENGTH(K),K=1,NSEG)
      WRITE(9,930) (ACS(K),K=1,NSEG)
      WRITE(9,940) (WIDTH(K),K=1,NSEG)
C
C          OUTPUT WEATHER DATA
C
      WRITE(9,945) (CHDIR(K),K=1,NSEG)
      WRITE(9,947) (SLOPE(K),K=1,NSEG)
      WRITE (9,950)
      TIME=TSTART
      DO 40 J=1,NWEATHR
      TIME=TIME+TWEATHR
      IF(TIME.GT.24.) TIME=TIME-24.
   40 WRITE(9,960) TIME,W(J),WDIR(J),PA(J)
C
C          OUTPUT D.O. MEASUREMENTS
C
      WRITE (9,970)
      NPRINT=AMAXO(NDATA,NUDATA)
      DO 50 J=1,NPRINT
   50 WRITE(9,980)TMEAS(1,J),CT(1,J),TMEAS(2,J),CT(2,J)
      CALL RESTIME(TWEATHR)
      CALL CINFLOW(NUDATA,NFLAG)
      IF(NFLAG.EQ.0) GO TO 60
      CALL CPLOT(NUDATA)
   60 CALL TEMP(NWEATHR)
      CALL RESPHO(DAY,DLAT,DMERID,DLONG,RM,NWEATHR,PHOLAG)
      STOP
  800 FORMAT(8F10.4)
  805 FORMAT(8E10.3)
  810 FORMAT(16I5)
  815 FORMAT(12F6.2)
  820 FORMAT(16F5.1)
  822 FORMAT(8E10.2)
  825 FORMAT(6A10)
  830 FORMAT(12F5.2)
 835  FORMAT(12F5.0)
  900 FORMAT(///10X,'ESTIMATION OF CHANNEL COMMUNITY PHOTOSYNTHETIC AND'
     $,' RESPIRATORY RATES'//12X,'BY NUMERICALLY ROUTING DIEL ',
     $'DISSOLVED OXYGEN MEASUREMENTS'//34X,'BETWEEN TWO STATIONS'//35X,
     $'STARTING DATE =',2A10)
  901 FORMAT(///48X,A10)
 905  FORMAT(//10X,'LIST OF SYMBOLS:'//10X,'C = D.O.CONCENTRATION ',
     $'G/M**3)'/10X,'DSTAR = DIMENSIONLESS LONGITUDINAL DISPERSION ',
     $'NUMBER'/10X,'EPS = COEFFICIENT WHICH SPECIFIES TIME STEP METHOD '
     $/16X,'(1.0 FOR FULLY IMPLICIT, 0.5 FOR CRANK-NICOLSON IMPLICIT)'
     $/10X,'P = PHOTOSYNTHETIC RATE OF CHANNEL REACH (G/(M*M*HR))'
     $/10X,'T = WATER TEMPERATURE (DEG. C)'/10X,
     $'TR = HYDRAULIC RESIDENCE TIME OF CHANNEL REACH (HR)')
  907 FORMAT(//10X,'INPUT DATA'//10X,'COMPUTATIONAL TIME INCREMENT =',
     $F6.0,' SEC'/10X,'COMPUTATIONAL DISTANCE INCREMENT =',F5.1,' M'/
     $10X,'EPS =',F5.2/10X,'DSTAR =',F5.2/10X,
     $'MAXIMUM ERROR IN R OR P FOR ITERATION CONVERGENCE =',F6.4,
     $' G/(M*M*HR)'/10X,'MAXIMUM ITERATIONS =',I3/10X,
     $'CONSTANT FOR ARRHENIUS RELATION =',F6,3/10X,'CONSTANT ',
     $'REPRESENTATING RESPIRATION INHIBITION DUE TO LOW D. O. CONC. ='
     $,F5.2,' G/M**3'/10X,'ORDER OF EQUATION FIT TO UPSTREAM D. O. ',
     $'MEASUREMENTS =',I2)
  910 FORMAT(//10X,*INPUT DATA FOR EACH SEGMENT*//15X,*SEGMENT NUMBER*
     $,17I6)
  915 FORMAT(5X,'INITIAL D,O. AT UPSTREAM'/6X,'END OF SEGMENT (G/M**3) '
     $,17F6.2)
  920 FORMAT(5X,*SEGMENT LENGTH (M)*,7X,17F6.1)
  930 FORMAT(5X,'CROSS-SECT. AREA (M*M)    ',17F6.2)
  940 FORMAT(5X,*SURFACE WIDTH (M)*,8X,17F6.2)
  945 FORMAT(5X,'SEGMENT DIRECTION (DEG)  ',17F6.0)
  947 FORMAT(5X,'WATER SURFACE SLOPE',7X,17F6.5)
  950 FORMAT(//20X,*WEATHER DATA INPUT TO MODEL*//18X,*TIME     WIND
+*  ,*   WIND     AIR*/24X,*VELOCITY  DIRECTION PRESSURE*/25X,*(M/SEC)
+*  ,* (DEGREES)     (MB)*)
  960 FORMAT(18X,F5.2,F8.2,3F10.2)
  970 FORMAT(//15X,'MEASURED DISSOLVED OXYGEN (G/M**3)'//16X,*UPSTREAM*
     $,12X,*DOWNSTREAM*/16X,*TIME   D.O.          TIME   D.O.*)
  980 FORMAT (10X,2(F10.2,F7.2,3X))
      END
      SUBROUTINE RESTIME(TWEATHR)
C
C         THIS SUBROUTINE COMPUTES THE CHANNEL RESIDENCE TIME ASSOCIATED WITH
C         EACH DOWNSTREAM D.O. MEASUREMENT
C
      COMMON/A/ C(80,2),CO(500),CT(2,35),THEAS(2,35),CIE(80),NOR
      COMMON/B/ FC(80),PE(80),S(80),B(80),A(80),DL(80),FK(17,35)
      COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,BBAR,DSTAR,CKM,THETA,DBAR
      COMMON/D/ P(35),RESID(35),R(35),TR(35)
      COMMON/G/ Q(35),PA(35),W(35),WDIR(35),CK1,CK2,CK3,SLOPE(17)
      COMMON/H/ NDATA,ITERMAX,ERRMAX,TSTART,RUNTIME,ENDTIME,NDAYS
      DO 200 J=1,NDATA
      TR(J)=0.0
      JF=(TMEAS(2,J)-TSTART)/TWEATHR+0.99
      TIMJF=0.0
      DO 100 I=2,IX-1
      II=IX-I+1
      TR(J)=TR(J)+A(II)*DELX/Q(JF)/3600.
      TIMJF=TIMJF+A(II)*DELX/Q(JF)/3600.
      IF(TIMJF.LT.TWEATHR) GO TO 100
      TIMJF=TIMJF-TWEATHR
      JF=JF-1
      IF(JF.EQ.0) GO TO 150
  100 CONTINUE
      TR(J)=TR(J)+A(1)*DELX/Q(JF)/3600./2.
  150 IF(TMEAS(2,J)-TR(J).LT.TSTART) TR(J)=TMEAS(2,J)-TSTART
  200 CONTINUE
      RETURN
      END
      SUBROUTINE CINFLOW(NUDATA,NFLAG)
C
C         THIS SUBROUTINE FITS AN ALGEBRAIC EQN. OF ORDER NOR THROUGH THE
C         UPSTREAM MEASURED D.O. CONCENTRATION. THE FITTED EQN. THEN
C         GIVES UPSTREAM D.O. CONC. AT EACH TIME INCREMENT.
C
      COMMON/A/ C(80,2),CO(500),CT(2,35),TMEAS(2,35),CIE(80),NOR
      COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,BBAR,DSTAR,CKM,THETA,DBAR
      COMMON/H/ NDATA,ITERMAX,ERRMAX,TSTART,RUNTIME,ENDTIME,NDAYS
      DIMENSION AB(9,9),TM(9),CM(9),SCRATCH(9),TIM(500)
      NT=(RUNTIME+1.00)*3600./DTIME
      LF=FLOAT(NT)/5.+0.99
      TIME=TSTART
      NEQ=NOR+1
      NEK=NEQ+1
      J=1
      IFLAG=0
      DO 200 K=1,NT
      TIM(K)=TIME
      IF(J.GE.NUDATA) GO TO 150
      IF(TIME.LE.TMEAS(1,J+1)) GO TO 5
      J=J+1
      IF(J.GE.NUDATA) GO TO 150
      IFLAG=0
    5 IF(IFLAG.EQ.1) GO TO 150
      DO 3 I=1,NEQ
    3 AB(I,1)=1.0
      IF(J-NEK/2.LT.0) GO TO 20
      IF(NUDATA-J-NEK/2.LT.0) GO TO 40
      IF=NEQ
      DO 10 I=1,IF
      IJ=J+I-NEQ/2
      CM(I)=CT(1,IJ)
   10 TM(I)=TMEAS(1,IJ)
      GO TO 100
   20 IF=NEK/2+J
      DO 30 I=1,IF
      CM(I)=CT(1,I)
   30 TM(I)=TMEAS(1,I)
      GO TO 100
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   40 IF=NEK/2+NUDATA-J
      DO 50 I=1,IF
      IJ=NUDATA-IF+I
      CM(I)=CT(1,IJ)
   50 TM(I)=TMEAS(1,IJ)
  100 CONTINUE
      DO 120 I=1,IF
      AB(I,2)=TM(I)
      IF(IF.LT.3) GO TO 120
      DO 110 II=3,IF
  110 AB(I,II)=TM(I)*AB(I,II-1)
  120 AB(I,IF+1)=CM(I)
C
C         MXLNEQ = UNIVERSITY OF MINNESOTA SUBROUTINE FOR INVERSION OF A
C                  LINEAR MATRIX
C
      CALL MXLNEQ(AB,IF,9,DET,JRANK,1.E-40,SCRATCH,-1)
      IFLAG=1
  150 SUM=AB(1,IF+1)+AB(2,IF+1)*TIME
      IF(IF.LT.3) GO TO 170
      DO 160 I=3,IF
  160 SUM=SUM+AB(I,IF+1)*TIME**(I-1)
  170 CO(K)=SUM
      TIME=TIME+DTIME/3600.
  200 CONTINUE
      IF(NFLAG.EQ.0) RETURN
      WRITE(9,900)
      DO 300 L=1,LF,40
      WRITE(9,910)
      DO 300 I=1,40
      K=I+(L-1)*5
  300 WRITE(9,920) ((TIM(K+J),CO(K+J)),J=1,200,40)
      RETURN
  900 FORMAT(///20X,'INFLOW DISSOLVED OXYGEN CONCENTRATION (G/M**3)')
  910 FORMAT(//16X,'TIME     D.O.          TIME     D.O.          TIME     D.O.
+'  ,'          TIME     D.O.          TIME     D.O.'/)
  920 FORMAT(10X,5(5X,F5.2,F10.4))
      END
      SUBROUTINE CPLOT(NUDATA)
C
C         THIS SUBROUTINE PLOTS UPSTREAM AND DOWNSTREAM MEASURED D.O.
C         CONC. AND THE CURVE FITTED TO THE UPSTREAM D.O. MEASUREMENTS.
C
      COMMON/A/ C(80,2),CO(500),CT(2,35),TMEAS(2,35),CIE(80),NOR
      COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,BBAR,DSTAR,CKM,THETA,DBAR
      COMMON/H/ NDATA,ITERMAX,ERRMAX,TSTART,RUNTIME,ENDTIME,NDAYS
      COMMON/I/ IT(6),IH(6),IY(6)
      DIMENSION ICH(3),X(101),Y(101),SCR(700)
      NT=(RUNTIME+0.99)*3600./DTIME
      DATA ICH(1)/10HOOOOOOOOOO/,ICH(2)/10HDDDDDDDDDD/,ICH(3)
     $/10H**********/
      WRITE(9,900)
      DO 10 I=1,NDATA
      X(I)=TMEAS(2,I)
   10 Y(I)=CT(2,I)
C
C         SCLPLT = UNIVERSITY OF MINNESOTA SYSTEM PRINT-PLOT SUBROUTINE
C
      CALL SCLPLT(X,Y,-NDATA,ICH(2),DU,DU,SCR)
      NP=0
      DO 20 I=1,NT,NT/100+1
      NP=NP+1
      X(NP)=TSTART+FLOAT(I-1)*DTIME/3600.
   20 Y(NP)=CO(I)
      CALL SCLPLT(X,Y,-NP,ICH(3),DU,DU,SCR)
      DO 30 I=1,NUDATA
      X(I)=TMEAS(1,I)
   30 Y(I)=CT(1,I)
      CALL SCLPLT(X,Y,-NUDATA,ICH(1),DU,DU,SCR)
      CALL SCLPLT(DU,DU,0,IT,IH,IY,SCR)
      RETURN
  900 FORMAT(////20X,'SCALE PLOT OF MEASURED UPSTREAM DISSOLVED OXYGEN ',
     $'CONCENTRATION (O),'/34X,'MEASURED DOWNSTREAM DISSOLVED OXYGEN ',
     $'CONCENTRATION (D),AND'/34X,'CURVE FIT TO MEASURED UPSTREAM ',
     $'OXYGEN CONCENTRATIONS (*)'///)
      END
      SUBROUTINE TEMP(NWEATHR)
C
C         THIS SUBROUTINE ESTIMATES WATER TEMPERATURE FOR EACH SEGMENT
C         WHERE INPUT VALUE = 0
C
      COMMON/E/ T(17,35),SE(17,35),RK(17,35),CS(17,35),NSEG,IDSEG(17)
     $,ISEG(17),SLENGTH(17),CHDIR(17)
      DO 100 J=1,NWEATHR
      I2=1
      I=1
    5 I1=I2
   10 I=I+1
      IF(I.EQ.NSEG+2) GO TO 50
      IF(T(I,J).LT.0.01) GO TO 10
      I2=I
      IF(I2.EQ.I1+1) GO TO 5
      SUMA=0.0
      DO 20 K=I1,I2-1
   20 SUMA=SUMA+SLENGTH(K)
      SUMB=0.0
      DO 30 II=I1+1,I2-1
      K=I2-II+I1
      SUMB=SUMB+SLENGTH(K)
   30 T(K,J)=SUMB/SUMA*T(I1,J)+(1.-SUMB/SUMA)*T(I2,J)
      IF(I2.GT.NSEG) GO TO 80
      GO TO 5
   50 SUMR=0.0
      DO 60 K=I2+1,NSEG+1
      SUMB=SUMR+SLENGTH(K)
   60 T(K,J)=T(I2,J)+SUMB/SUMA*(T(I2,J)-T(I1,J))
   80 CONTINUE
      DO 100 K=1,NSEG
      T(K,J)=(T(K,J)+T(K+1,J))/2.
  100 CONTINUE
      RETURN
      END
      SUBROUTINE RESPHO(DAY,DLAT,DMERID,DLONG,RM,NWEATHR,PHOLAG)
C
C         THIS SUBROUTINE ESTIMATES TOTAL COMMUNITY RESPIRATORY AND
C         PHOTOSYNTHETIC RATES FROM SUCCESSIVE ITERATIONS ON ROUTED
C         DISSOLVED OXYGEN CONCENTRATION.
C
      COMMON/A/ C(80,2),CO(500),CT(2,35),TMEAS(2,35),CIE(80),NOR
      COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,BBAR,DSTAR,CKM,THETA,DBAR
      COMMON/D/ P(35),RESID(35),R(35),TR(35)
      COMMON/E/ T(17,35),SE(17,35),RK(17,35),CS(17,35),NSEG,IDSEG(17)
     $,ISEG(17),SLENGTH(17),CHDIR(17)
      COMMON/H/ NDATA,ITERMAX,ERRMAX,TSTART,RUNTIME,ENDTIME,NDAYS
      DIMENSION JRISF(5),JSET(5)
      EXTERNAL ROUTE,PRNOUT
C
C         DETERMINE SUNRISE AND SUNSET TIMES
C
      SUNDEC=0.409*COS(0.0172*(172.-DAY))
      HOURO=ACOS(-SIN(DLAT)*SIN(SUNDEC)/COS(DLAT)/COS(SUNDEC))
      DP=6.18*(DAY-1.)/365.24
      ET=0.12357*SIN(DP)-0.004289*COS(DP)+0.153809*SIN(2.*DP)
     $+0.060783*COS(2.*DP)
      SUNRISE=-HOURO*12./3.14+12.+ET+(DMERID-DLONG)/15.
      SUNSET=12.+HOURO*12./3.14+ET+(DMERID-DLONG)/15.
      ENDPHO=SUNSET+PHOLAG
C
C         JRISE(L) IDENTIFIES LAST DOWNSTREAM D.O. MEAS. BEFORE SUNRISE
C         JSET(L) IDENTIFIES FIRST DOWNSTREAM D.O. MEAS. AFTER SUNSET +
C                 RESIDENCE TIME
C
      LS=1
      DO 5 L=1,NDAYS+1
      JRISE(L)=0
    5 JSET(L)=0
      DO 10 J=1,NDATA-1
      L=IFIX(TMEAS(2,J)/24.)+1
       TRISE=SUNRISE+FLOAT(24*(L-1))
      IF(TMEAS(2,J).LE.TRISE.AND.TMEAS(2,J+1).GT.TRISE) JRISE(L)=J
      TSET=ENDPHO+FLOAT(24*(L-1))+TR(J)
      IF(TMEAS(2,J).LE.TSET.AND.TMEAS(2,J+1).GT.TSET) GO TO 7
      GO TO 10
    7 LS=L
      JSET(L)=J+1
   10 CONTINUE
      IF(JSET(L).EQ.0)JSET(L)=NDATA
      IF(JRISE(LS+1).EQ.0.AND.JSET(LS).LT.NDATA) JRISE(LS+1)=NDATA
C
C         SET UP INITIAL VALUES
C
      DO 15 J=1,NDATA+1
   15 P(J)=0.0
      ITER=1
C
```

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C
C       IF THE D.O. SURVEY BEGAN AFTER DAWN, GO TO 80
C
      IF(JRISE(1).EQ.0) GO TO 80
   30 DO 40 I=1,IX+1
      C(I,1)=CIE(I)
   40 C(I,2)=CIE(I)
C
C       ROUTE D.O. BETWEEN STARTING TIME AND SUNRISE TO GET A BETTER
C       ESTIMATE OF RESPIRATORY RATE
C
      CALL ROUTE (TSTART,SUNRISE,RM)
      IFLAG=0
      SUM=0.0
C
C       DETERMINE NEW STANDARD RESPIRATORY RATE
C
      DO 60 J=1,JRISE(1)
      CM=(CT(1,J)+CT(2,J))/2.
      TM=(T(1,J)+T(NSEG,J+1))/2.
   60 SUM=SUM+RESID(J)/TR(J)*DBAR*(1.+CKM/CM)/THETA**(TM-20.)
      ERRM=SUM/FLOAT(JRISE(1))
      IF(ABS(ERRM).GT.ERRMAX) IFLAG=1
      RM=RM-ERRM
      WRITE(9,900) RM,ERRM
      IF(IFLAG.EQ.1) GO TO 30
C
C       ROUTE D.O. TO ASSIGN PHOTOSYNTHETIC RATES
C
   80 DO 90 I=1,IX+1
      C(I,1)=CIE(I)
   90 C(I,2)=CIE(I)
      CALL ROUTE(TSTART,ENDTIME,RM)
      JFLAG=0
      ITER=ITER+1
C
C       ASSIGN NEW PHOTOSYNTHETIC RATES
C
      DO 100 L=1,NDAYS
      DO 100 J=JRISE(L)+1,JSET(L)
      PERR=RESID(J)/TR(J)*DBAR
      P(J)=P(J)+PERR
      IF(P(J).GE.0.0) GO TO 100
      PERR=PERR-P(J)
      P(J)=0.0
  100 IF(ABS(PERR).GT.ERRMAX) JFLAG=1
      IF(JFLAG.EQ.1) GO TO 80
      DO 105 I=1,IX+1
C
C       ROUTE D.O. TO DETERMINE STANDARD RESPIRATORY RATE
C
      C(I,1)=CIE(I)
  105 C(I,2)=CIE(I)
      CALL ROUTE(TSTART,ENDTIME,RM)
C
C       ASSIGN NEW STANDARD RESPIRATORY RATE
C
      SUM=0.0
      N=0
      IF(JRISE(1).LT.1) GO TO 108
      DO 107 J=1,JRISE(1)
      N=N+1
      CM=(CT(1,J)+CT(2,J))/2.
      TM=(T(1,J)+T(NSEG,J+1))/2.
  107 SUM=SUM+RESID(J)/TR(J)*DBAR*(1.+CKM/CM)/THETA**(TM-20.)
  108 DO 115 L=1,NDAYS
      IF(JRISE(L+1).EQ.0)GO TO 115
      DO 110 J=JSET(L)+1,JRISE(L+1)
      N=N+1
      CM=(CT(1,J)+CT(2,J))/2.
      TM=(T(1,J)+T(NSEG,J+1))/2.
  110 SUM=SUM+RESID(J)/TR(J)*DBAR*(1.+CKM/CM)/THETA**(TM-20.)
  115 CONTINUE
      ERRM=SUM/FLOAT(N)
      WRITE(9,900) RM,ERRM,ITER
      IF(ABS(ERRM).GT.ERRMAX) JFLAG=1
      RM=RM-ERRM
      IF(ITER.GE.ITERMAX) GO TO 200
      IF(JFLAG.EQ.1) GO TO 80
  200 CONTINUE
      RM=RM+ERRM
      CALL PRNOUT(RM,ITER,DATE,SUNRISE,SUNSET,NWEATHR)
      RETURN
  900 FORMAT(/10X,*STANDARD RESPIRATION RATE = *,F8.4,' G/(M*M*HR) AT
+'  ,'20 DEG C      MEAN ERROR =',F8.4,I8,' ITERATIONS')
      END
      SUBROUTINE ROUTE(STIME,FTIME,RM)
C
C        THIS SUBROUTINE NUMERICALLY ROUTES (PREDICTS) D.O. THROUGH THE
C        CHANNEL REACH WITH THE GIVEN STANDARD RESPIRATORY RATE AND
C        PHOTOSYNTHETIC RATES
C
      COMMON/A/ C(80,2),CO(500),CT(2,35),THEAS(2,35),CIE(80),NOR
      COMMON/B/ FC(80),PE(80),S(80),B(80),A(80),DL(80),FK(17,35)
      COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,RBAR,DSTAR,CKM,THETA,DBAR
      COMMON/D/ P(35),RESID(35),R(35),TR(35)
      COMMON/E/ T(17,35),SE(17,35),RK(17,35),CS(17,35),NSEG,IDSEG(17)
     $,ISEG(17),SLENGTH(17),CHDIR(17)
      COMMON/F/ F(80),G(80),EPS,FEPS
      COMMON/G/ Q(35),PA(35),W(35),WDIR(35),CK1,CK2,CK3,SLOPE(17)
      DIMENSION CITER(80),COLD(80),TEM(17)
      EXTERNAL SURFLUX,TDMA,QRATE
C
C        ASSIGN PARAMETERS INTERNAL TO THIS SUBROUTINE
C
      TIME=STIME
      HDTIME=DTIME/7200.+.0001
      NT=(FTIME-STIME)/FLOAT(JWEATHR)+0.999
      C(1,1)=CO(1)
      JP=1
C
C        BEGIN MAIN LOOP. ONE ITERATION FOR EACH INPUT OF WEATHER DATA
C        AND WATER TEMPERATURES
C
      R(JP)=0.0
      IR=0
      DO 300 LOOP=1,NT
      DO 10 I=1,IX
   10 COLD(I)=C(I,1)
C
C        CALL D.O. SURFACE EXCHANGE SUBROUTINE
C
      CALL SURFLUX(LOOP,EPS)
C
C        SECOND LOOP. ONE ITERATION EACH HOUR
C
      DO 100 ILOOP=1,JWEATHR
C
C        DETERMINE WATER TEMP. FOR EACH HOUR
C
      DO 20 I=1,NSEG+1
      FR=FLOAT(ILOOP)/FLOAT(JWEATHR)
   20 TEM(I)=T(I,LOOP)*(1.-FR)+T(I,LOOP+1)*FR
C
C        ASSIGN LONGITUDINAL DISPERSION COEFFICIENT FOR EACH DIST.
C
                                                          INCREMENT
      DL(1)=DSTAR*Q(LOOP)/RBAR
      DO 30 I=1,IX
      DL(I+1)=DL(1)
C
C        ASSIGN PARAMETERS FOR SOLUTION OF FINITE DIFFERENCE MATRIX (GRID
C        PECLET AND GRID COURANT NUMBERS)
C
      FC(I)=Q(LOOP)*DTIME/(A(I)+A(I+1))/DELX*2.
   30 PE(I)=2.*Q(LOOP)*DELX/(A(I)*DL(I)+A(I+1)*DL(I+1))
      FC(1)=FC(1)*2.
      FC(IX-1)=FC(IX-1)*2.
      FC(IX)=FC(IX)*2.

C
C        THIRD LOOP. ONE ITERATION FOR EACH TIME INCREMENT, DTIME.
C
      DO 100 J=1,JTIME
      TIME=TIME+DTIME/3600.
      C(IX+1,1)=C(IX,1)*2.-C(IX-1,1)
      JT=JTIME*((LOOP-1)*JWEATHR+ILOOP-1)+J
      C(1,2)=CO(JT)
C
C     ****************************************************
C        TRI-DIAGONAL MATRIX ALGORITHM
C        THIS ALGORITHM SOLVES FOR D.O. CONC. AT NEW TIME INCREMENT
C
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```
      I=2
      K=1
      ISUM=I
      RESP=RM*THETA**(TEM(K)-20.)*C(I,1)/(C(I,1)+CKM)
      R(JP)=R(JP)+RESP
      IR=IR+1
      CALL TDMA(I,AK,BK,CK,DK,RESP,JP,LOOP,K)
      G(I)=(DK+AK*C(1,2))/BK
      F(I)=-CK/BK
      DO 50 I=3,IX-1
      ISUM=ISUM+1
      IF(ISUM.LE.ISEG(K)) GO TO 49
      ISUM=1
      K=K+1
   49 CONTINUE
      RESP=RM*THETA**(TEM(K)-20.)*C(I,1)/(C(I,1)+CKM)
      R(JP)=R(JP)+RESP
      IR=IR+1
      CALL TDMA(I,AK,BK,CK,DK,RESP,JP,LOOP,K)
      G(I)=(DK+AK*G(I-1))/(BK+AK*F(I-1))
   50 F(I)=-CK/(BK+AK*F(I-1))
      I=IX
      RESP=RM*THETA**(TEM(K)-20.)*C(I,1)/(C(I,1)+CKM)
      R(JP)=R(JP)+RESP
      IR=IR+1
      CALL TDMA(I,AK,BK,CK,DK,RESP,JP,LOOP,K)
      G(I)=((AK-CK)*G(I-1)+DK)/(BK-2.*CK+(AK-CK)*F(I-1))
      C(I,2)=G(I)
      DO 70 I=1,IX-2
   70 C(IX-I,2)=G(IX-I)-F(IX-I)*C(IX-I+1,2)
      DO 80 I=1,IX
   80 C(I,1)=C(I,2)
C
C     ****************************************************
C         IS IT TIME TO COMPARE WITH MEASUREMENTS?
C
      IF(TIME.LT.TMEAS(2,JP)-HDTIME.OR.TIME.GT.TMEAS(2,JP)+HDTIME-.0002)
     $GO TO 100
C
C         ASSIGN RESIDUALS
C
      RESID(JP)=CT(2,JP)-C(IX,2)
      R(JP)=R(JP)/FLOAT(IR)
      JP=JP+1
      R(JP)=0.0
      IR=0
  100 CONTINUE
      IS=1+ISEG(1)/2
      DO 110 K=1,NSEG
      SE(K,LOOP)=S(IS)-RK(K,LOOP)*(C(IS,2)+COLD(IS))/2./B(IS)*A(IS)
  110 IS=IS+(ISEG(K)+ISEG(K+1))/2
  300 CONTINUE
      RETURN

      END
      SUBROUTINE SURFLUX(JLOOP,EPS)
C
C         THIS SUBROUTINE COMPUTES SURFACE D.O. EXCHANGE
C
      COMMON/A/ C(80,2),CO(500),CT(2,35),TMEAS(2,35),CIE(80),NOR
      COMMON/B/ FC(80),PE(80),S(80),B(80),A(80),DL(80),FK(17,35)
      COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,BBAR,DSTAR,CKM,THETA,DBAR
      COMMON/E/ T(17,35),SE(17,35),RK(17,35),CS(17,35),NSEG,IDSEG(17)
     $,ISEG(17),SLENGTH(17),CHDIR(17)
      COMMON/G/ Q(35),PA(35),W(35),WDIR(35),CK1,CK2,CK3,SLOPE(17)
      REAL KEU,KVIS
      J=JLOOP
      I=ISEG(1)/2+1
      DO 20 K=1,NSEG
      CS(K,J)=(14.652-0.410222*T(K,J)+0.00799*T(K,J)*T(K,J)-7.777E-5
     $*T(K,J)**3)*PA(J)/1013.
      WL=W(J)*ABS(COS(3.14/180.*(CHDIR(K)-WDIR(J))))
      VSHEAR=SQRT(9.8*DBAR*SLOPE(K))
      KVIS=1.79E-6/(1.+.03368*T(K,J)+.000221*T(K,J)**2)
      DM=2.03E-9*1.035**(T(K,J)-20.)
      RD=DM/KVIS
      RES=VSHEAR*DBAR/KVIS
      REP=CK3*RES
      CHI=SQRT(1.+(RD+CK2*WL**5)/CK1/4./REP)
      RK(K,J)=4.*CK1*CHI*VSHEAR/ALOG((CHI+1.)/(CHI-1.))*3600./DBAR
      FK(K,J)=RK(K,J)*EPS*DTIME/3600.
   20 I=I+(ISEG(K)+ISEG(K+1))/2
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```
      K=1
      IS=1
      DO 40 K=1,NSEG
      DO 30 I=IS,IS+ISEG(K)-1
   30 S(I)=RK(K,J)*CS(K,J)/B(I)*A(I)
   40 IS=IS+ISEG(K)
      S(IS)=S(IS-1)
      RETURN
      END
      SUBROUTINE TDMA(I,AK,BK,CK,DK,RESP,JP,J,K)
C
C         THIS SUBROUTINE SETS UP PARAMETERS FOR THE TRI-DIAGONAL
C         MATRIX ALGORITHM
C
      COMMON/A/ C(80,2),CO(500),CT(2,35),TMEAS(2,35),CIE(80),NOR
      COMMON/B/ FC(80),PE(80),S(80),B(80),A(80),DL(80),FK(17,35)
      COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,BBAR,DSTAR,CKM,THETA,DBAR
      COMMON/D/ P(35),RESID(35),R(35),TR(35)
      COMMON/F/ F(80),G(80),EPS,FEPS
      AK=FC(I-1)*EPS*(1.+AMAX1(0.,(1.-0.1*PE(I-1))**5/PE(I-1)))
      CK=EPS*FC(I)*AMAX1(0.,(1.-0.1*PE(I))**5/PE(I))
      BK=1.+AK+CK+FK(K,J)
      DK=C(I,1)+FEPS*(AK*C(I-1,1)-(AK+CK+FK(K,J))*C(I,1)+CK*C(I+1,1))
     $+(S(I)-RESP+P(JP))*B(I)*DTIME/A(I)/3600.
      RETURN
      END
      SUBROUTINE PRNOUT(RM,ITER,DATE,SUNRISE,SUNSET,NWEATHR)
C
C         THIS SUBROUTINE OUTPUTS THE RESULTS OF THE D.O. ROUTING MODEL
C
      COMMON/A/ C(80,2),CO(500),CT(2,35),TMEAS(2,35),CIE(80),NOR
      COMMON/C/ DELX,DTIME,IX,JTIME,JWEATHR,BBAR,DSTAR,CKM,THETA,DBAR
      COMMON/D/ P(35),RESID(35),R(35),TR(35)
      COMMON/E/ T(17,35),SE(17,35),RK(17,35),CS(17,35),NSEG,IDSEG(17)
     $,ISEG(17),SLENGTH(17),CHDIR(17)
      COMMON/F/ F(80),G(80),EPS,FEPS
      COMMON/G/ Q(35),PA(35),W(35),WDIR(35),CK1,CK2,CK3,SLOPE(17)
      COMMON/H/ NDATA,ITERMAX,ERRMAX,TSTART,RUNTIME,ENDTIME,NDAYS

      WRITE(9,900)
      WRITE(9,920) RM,SUNRISE,SUNSET,ITER
      WRITE(9,975)
      WRITE(9,930)
      DO 50 J=1,NDATA
      TIME=TMEAS(2,J)
   30 IF(TIME.LT.24.) GO TO 40
      TIME=TIME-24.
      GO TO 30
   40 WRITE(9,940) TIME,P(J),R(J),RESID(J),TR(J)
 50   CONTINUE
      J=2
      STIME=TSTART
      TOTALR=R(1)*(TMEAS(2,1)-TSTART)
      TOTALP=P(1)*(TMEAS(2,1)-TSTART)
      DO 80 IDAY=1,NDAYS
   60 TOTALR=TOTALR+R(J)*(TMEAS(2,J)-TMEAS(2,J-1))
      TOTALP=TOTALP+P(J)*(TMEAS(2,J)-TMEAS(2,J-1))
      IF(TMEAS(2,J)-STIME.GE.FLOAT(24*IDAY)) GO TO 70
      IF(J.EQ.NDATA)GO TO 70
      J=J+1
      GO TO 60
   70 TOTALR=TOTALR+R(J)*(24.-TMEAS(2,J)+STIME)
      PR=TOTALP/TOTALR
      WRITE(9,935)IDAY,TOTALR,TOTALP,PR
      STIME=TMEAS(2,J)
      J=J+1
      TOTALR=0.0
   80 TOTALP=0.0
      TIME=TSTART
      WRITE(9,945)
      WRITE(9,950) (IDSEG(K),K=1,NSEG)
      DO 100 J=1,NWEATHR
      TIME=TIME+FLOAT(JWEATHR)
      IF(TIME.GT.24.) TIME=TIME-24.
      WRITE(9,955) TIME,Q(J)
      WRITE(9,960)(SE(K,J),K=1,NSEG)
      WRITE(9,970)(RK(K,J),K=1,NSEG)
      WRITE(9,980)(CS(K,J),K=1,NSEG)
      WRITE(9,990)(T(K,J),K=1,NSEG)
  100 CONTINUE
      RETURN
 900 FORMAT(///'**************************************************************'
     $///5X,'RESULTS OF COMPUTATIONS:')
 920 FORMAT(//10X,'STANDARD RESPIRATORY RATE =',F7.4,' G/(M*M*HR) AT 20'
     $,' DEG C'/10X,'SUNRISE TIME =',F6.2/10X,'SUNSET TIME =',F6.2/
     $10X,I2,' ITERATIONS'//)
 925 FORMAT(10X,'ROUTED TOTAL COMMUNITY PHOTOSYNTHETIC AND RESPIRATORY'
     $,' RATES')
930  FORMAT(26X,'TIME         P          R      RESIDUAL    TR'/32X,
     $'----G/(M*M*HR)----    G/M**3      HR')
 935 FORMAT(///15X,'DAY',I3/15X,'TOTAL DAILY RESPIRATION = ',F7.4,
     $'G/M**2'/15X,'TOTAL DAILY PHOTOSYNTHESIS = ',F7.4,'G/M**2'/15X,
     $'P/R RATIO =',F7.4)
940  FORMAT(20X,F10.2,4F10.3)
 945 FORMAT(///10X,'COMPUTED VALUES OF SURFACE D. O. EXCHANGE ',
     $'(G/(M*M*HR)),'/29X,'SURFACE EXCHANGE COEFFICIENT (/HR),'/29X,
     $'SATURATION D.O. CONCENTRATION (G/M**3),'/29X,
     $'AND WATER TEMPERATURE (DEG. C)'/29X,'FOR EACH CHANNEL SEGMENT')
950  FORMAT(///10X,*SECTION NO.     *12I7)
955  FORMAT(/15X,*TIME =*,F6.2,*  FLOW RATE =*,F8.4,' (M**3/SEC)')
960  FORMAT(10X,*SURFACE EXCH.  *,12F7.4)
970  FORMAT(10X,*SE COEFFICIENT *,12F7.4)
980  FORMAT(10X,*SAT. D.O. CONC.*,12F7.2)
990  FORMAT(10X,*TEMPERATURE    *,12F7.2)
     END
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TYPING GUIDE SHEET
BEGIN FIRST LINE OF TEXT HERE
DROPPED HEAD; BEGIN SECTIONS HERE
CENTER OF PAGE
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SAMPLE INPUT DATA

```
  178.      .01     720.       25.       400.      0.15      23.00     2.0
     2.00     45.      93.       90.      0.001      1.0       0.0       1.045
             213.      744.
   5.44E-4    3.8E-5    1.49E0
    4   12   11   20    6    1    3    0
 14.2  2.6 14.7  2.4 14.2  2.1 13.4  2.5
 11.3  5.7 10.6  5.7 10.0  5.3 10.7  5.9
  66.  66.  66.  52.  38.  13.   3. 351. 351. 351.
 100. 100. 100. 100. 100. 100. 100. 100. 100. 100.
   3.05E-4   3.05E-4   3.05E-4   3.05E-4   3.05E-4   3.05E-4
CHANNEL 6   JUNE 27, 1979
MEASURED AND UPSTREAM DISSOLVED OXYGEN CONCENTRATIONS
     TIME OF DAY
DISSOLVED OXYGEN CONCENTRATION PPM
  7.20  6.70  6.20  5.80  5.4
 19.2                19.0
 19.1                18.4
 19.1                18.8
 19.4                20.2
 19.9                21.7
 20.4                22.8
 21.0                23.5
 21.4                23.2
 21.5                22.2
 21.5                21.2
 21.2                20.6
 21.0                20.3
 20.8                20.0
  .42  .83  .85  .85 2.00 2.15 2.06 2.15  .42  .07  .00  .00
  355  200  200   30   30   40   35   35   35   35   35   35
 7.2  7.1  7.15 7.9  8.1  8.45 8.4  8.5  7.95 7.4  7.1  7.1
  308  504  658  909 1102 1307 1508 1703 1902 2102 2300 2503
 5.5  6.7 10.5 14.0516.4 15.2513.4510.8  7.1  5.5  5.25
  516  708  921 1112 1318 1518 1710 1910 2109 2307 2511
```

APPENDIX B

INSTRUCTIONS FOR THE USE OF THE DISSOLVED OXYGEN ROUTING MODEL (DORM) COMPUTER PROGRAM

DORM is designed to be a general model for diel curve analysis. All parameters are specified from the TAPE8 input file. If cards are used as input, the first line of the program must be changed. All output is placed on file RESULTS, which may then be examined with a text editor. This is useful for program debugging and for making more than one copy of the output if so desired. There is no choice of equations to be used for respiratory rate or D.O. surface exchange. New equations may be specified by changing the appropriate lines in the computer program. The user should note that D* must be greater than zero, or the numerical solution algorithm will not work. A non-dispersive stream may be modelled with a small D* value.

The TAPE8 input file is examined below on a line by line basis. The format for each line is given in parenthesis. Sample input data from Appendix A are given in brackets.

Line 1(8F 10.4)DAY, DSTAR, DTIME, DELX, TLENGTH, RM, RUNTIME, TWEATHR

DAY = Julian day of the year for the first day with photosynthesis [178]
DSTAR = dimensionless longitudinal dispersion coefficient (must be greater than zero) [0.01]
= D_L* mean width/flow rate
DTIME = computational time increment (sec) [720]
DELX = computational distance increment (ft) [25]
TLENGTH = total length of stream reach (ft) [400]
RM = initial (first guess) standard respiratory rate at 20°C and large D.O. concentration (g/m^3) [0.15]
RUNTIME = total time of simulation (hr) [23.00]
TWEATHR = time between input of weather data and water temperatures (hr) [2.0]

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Line 2(8F 10.4) TSTART, DLAT, DLONG, DMERID, ERRMAX, EPA, PHOLAG, THETA

TSTART = starting time (hour of day) [2.00]
DLAT = latitude of study site (degrees) [45]
DLONG = longitude of study site (degrees) [93]
DMERID = longitude of the field study site's time zone meridian (degrees) [90]
ERRMAX = maximum allowable difference in photosynthetic or respiratory rates between successive iterations for convergence of diel curve routine ($g/m^2/hr$) [0.001]
EPS = coefficient for formulation of finite differences [1.0]
= 1.0 for fully implicit
= 0.5 for C-N implicit
= 0.0 for explicit
PHOLAG = lag in plant release of photosynthetically produced oxygen (hr). This parameter will delay the time of the day when photosynthesis ends [0.0]
THETA = temperature coefficient for the dependence of respiratory rate upon water temperature [1.045]

Line 3 (8F 10.4) CKM, FLOW, PRESSUR

CKM = Michaelis-Menten half-saturation coefficient for respiratory inhibition at low D.O. concentration (g/m^3) [0.0]
FLOW = average channel flow for the simulation time period (gpm) [213]
PRESSUR = average air pressure for the simulation time period (mm Hg) [744]

Line 4(8E 10.3)CK1, CK2, CK3

These are parameters for D.O. surface exchange

CK1 = A_1 [$5.44\text{x}10^{-4}$]
CK2 = A_7 [$3.8\text{x}10^{-5}$]
CK3 = A_5 [1.49]

Line 5(16I5)NSEG, NUDATA, ITERMAX, IDSEG(1) NDAYS, NOR, NFLAG

NSEG = number of segments in channel reach [4]
NUDATA = number of upstream D.O. measurements [12]
NDATA = number of downstream D.O. measurements [11]
ITERMAX = maximum number of iterations on D.O. routing routine allowed [20]
IDSEG(1) = Integer ID of the first upstream channel segment [6]
NDAYS = number of daylight days in the diel curve analysis [1]
NOR = order of curve extrapolation between upstream D.O. measurements [3]
NFLAG = 1 if curve interpolation and measured upstream D.O. concentration is to be output [0]

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Line 6(16F5.1) ACS(K), K=1, NSEG+1

ACS(K) = mean cross-sectional area of segment K (ft^2)
[ACS(1) = 14.2, ACS(5) = 14.2]

Line 7(16F5.1)WIDTH(K), K=1, NSEG+1

WIDTH(K) = mean surface width of segment K(ft)
[WIDTH(1) = 11.3, WIDTH(5) = 10.0]

Line 8(16F5.1) CHDIR(K), K=1, NSEG+1

CHDIR(K) = mean direction of the channel centerline in segment K (degrees, 0°=North)
[CHDIR(1) = 66, CHDIR(5) = 38.]

Line 9(16F5.1) SLENGTH(K), K=1, NSEG+1

SLENGTH(K) = length of channel segment K(ft)
[SLENGTH(1) = SLENGTH(5) = 100.]

Line 10(8E10.2)SLOPE(K), K=1, NSEG

SLOPE(K) = water surface slope of channel segment K
[SLOPE(1) = SLOPE(5) = 3.05×10^{-4}]

Line 11(6A10) CHANNEL, DATE, YEAR

CHANNEL = name of channel (A10) [CHANNEL 6]
DATE = starting month and day (A10) [JUNE 27,]
YEAR = year (A10) [1979]

Line 12-15(6A10)IT, IH, IY

IT = heading for output plot of D.O. measurements (6A10)
IH = heading of horizontal axis for output plot of D.O. measurements (6A10)
IY = heading of vertical axis for output plot of D.O. measurements (6A10)

Line 16(12F6.2) CI(K), K=1, NSEG+1

CI(K) = initial D.O. concentration in segment K
[CI(1) = 7.20, CI(5) = 5.4]

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Set 17. J=1, NWEATHR+1
(16F5.1) T(K, J) K=1, NSEG+1
[T(1,1) = 19.2, T(5,1) = 19.0]

T(K,J) = water temperature in segment K at weather data time step J(^{o}C)

If T(K,J) = 0.0, the actual T(K,J) is estimated through a piecewise linear approximation in the program. At each time step J, however, there must be at least two non-zero values of T(K,J)

There will be NWEATHR+1 lines in this set.
NWEATHR = IFIX (RUNTIME/TWEATHR+0.99); Number in parenthesis is

Set 18(12F5.2) W(J), J=1, NWEATHR

W(J) = wind velocity at weather data time step J(m/sec)
[W(1) = .42, W(12) = .00]

Set 19(12F5.0) WDIR(J), J=1, NWEATHR

WDIR(J) = wind direction at weather data time step J(degrees)
[WDIR(1) = 355, WDIR(12) = 35]

SET 20(12F5.2) CT(1,J), J=1, NUDATA

CT(1,J) = Jth upstream measured D.O. concentration (g/m^3)
[CT(1,1) = 7.2, CT(1,12) = 7.1]

Set 21(12F5.2) TMEAS(1,J), J=1, NUDATA

TMEAS(1,J) = time of measurement for Jth upstream D.O. concentration (hr.min)
[TMEAS(1,1) = 308, TMEAS(1, 12) = 2503]

Set 22(12F5.2) CF(2,J), J=1, NDATA

CT(2,J) = Jth downstream measured D.O. concentration (g/m^3)
[CT(2,1) = 5.5, CT(2,11) = 5.25]

Set 23(12F5.2) TMEAS(2,J), J=1, NDATA

TMEAS(2, J) = time of measurement for Jth downstream D.O. concentration (hr.min)
[TMEAS(2,1) = 516, TMEAS(2,11) = 2511]

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APPENDIX C

DORM Sample Output

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                                   CHANNEL 6


     ESTIMATION OF CHANNEL COMMUNITY PHOTOSYNTHETIC AND RESPIRATORY RATES

       BY NUMERICALLY ROUTING DIEL DISSOLVED OXYGEN MEASUREMENTS

                            BETWEEN TWO STATIONS

                             STARTING DATE = SEPTEMBER 17, 1979


     LIST OF SYMBOLS:

     C = D.O.CONCENTRATION G/M**3)
     DSTAR = DIMENSIONLESS LONGITUDINAL DISPERSION NUMBER
     EPS = COEFFICIENT WHICH SPECIFIES TIME STEP METHOD
           (1.0 FOR FULLY IMPLICIT, 0.5 FOR CRANK-NICOLSON IMPLICIT)
     P = PHOTOSYNTHETIC RATE OF CHANNEL REACH (G/(M*M*HR))
     T = WATER TEMPERATURE (DEG. C)
     TR = HYDRAULIC RESIDENCE TIME OF CHANNEL REACH (HR)


     INPUT DATA

     COMPUTATIONAL TIME INCREMENT =  720. SEC
     COMPUTATIONAL DISTANCE INCREMENT =  7.6 M
     EPS = 1.00
     DSTAR =  .01
     MAXIMUM ERROR IN R OR P FOR ITERATION CONVERGENCE = .0010 G/(M*M*HR)
     MAXIMUM ITERATIONS = 20
     CONSTANT FOR ARRHENIUS RELATION = 1.045
     CONSTANT REPRESENTATING RESPIRATION INHIBITION DUE TO LOW D. O. CONC. =   -0 G/M**3
     ORDER OF EQUATION FIT TO UPSTREAM D. O. MEASUREMENTS = 3


     INPUT DATA FOR EACH SEGMENT

          SEGMENT NUMBER     6     7     8     9    10
INITIAL D.O. AT UPSTREAM
 END OF SEGMENT (G/M**3)   8.80  8.80  8.85  8.90  8.90
SEGMENT LENGTH (M)         30.5  30.5  30.5  30.5
CROSS-SECT. AREA (M*M)     1.32   .24  1.37   .22
SURFACE WIDTH (M)          3.44  1.74  3.23  1.74
SEGMENT DIRECTION (DEG)     66.   66.   66.   52.
WATER SURFACE SLOPE       .00030.00030.00030.00030
```

```
           WEATHER DATA INPUT TO MODEL

         TIME       WIND     WIND      AIR
                  VELOCITY  DIRECTION PRESSURE
                  (M/SEC)  (DEGREES)    (MB)
         -4.00       .83     260.00    987.67
         -2.00      2.40     350.00    987.67
             0      1.06     350.00    987.67
          2.00       .68     260.00    987.67
          4.00       .32     270.00    987.67
          6.00      2.09     300.00    987.67
          8.00      2.90     330.00    987.67
         10.00      3.95     330.00    987.67
         12.00      3.33     320.00    987.67
         14.00      3.31     320.00    987.67
         16.00      2.79     360.00    987.67
         18.00      2.37      30.00    987.67
         20.00      2.37      30.00    987.67

      MEASURED DISSOLVED OXYGEN (G/M**3)

       UPSTREAM              DOWNSTREAM
        TIME    D.O.           TIME    D.O.
       -5.77    8.80          -3.87    7.25
       -3.90    8.35          -1.83    6.60
       -1.98    8.00            .22    6.50
         .08    7.90           2.12    6.40
        2.00    7.80           4.13    6.40
        4.00    7.80           6.15    6.35
        6.03    7.60           8.12    7.45
        8.00    8.05          10.12   10.10
       10.02    8.45          12.18   12.00
       12.07    9.35          14.15   13.10
       14.05    9.70          16.12   12.15
       16.02    9.45          18.20    9.30
       18.08    8.95              0       I

  STANDARD RESPIRATION RATE =    .2757 G/(M*M*HR) AT 20 DEG C     MEAN ERROR =  -.1257

  STANDARD RESPIRATION RATE =   .2805 G/(M*M*HR) AT 20 DEG C     MEAN ERROR =  -.0048

  STANDARD RESPIRATION RATE =   .2807 G/(M*M*HR) AT 20 DEG C     MEAN ERROR =  -.0002

  STANDARD RESPIRATION RATE =   .2807 G/(M*M*HR) AT 20 DEG C     MEAN ERROR =  -.0000       5 ITERATIONS


**************************************************

 RESULTS OF COMPUTATIONS:


  STANDARD RESPIRATORY RATE =  .2807 G/(M*M*HR) AT 20 DEG C
  SUNRISE TIME =  5.86
  SUNSET TIME = 17.99
   5 ITERATIONS


  ROUTED TOTAL COMMUNITY PHOTOSYNTHETIC AND RESPIRATORY RATES
                 TIME       P           R      RESIDUAL     TR
                      ----G/(M*M*HR)----        G/M**3      HR
                -3.87       0         .264       .063     2.101
                -1.83       0         .257      -.140     2.101
                  .22       0         .253       .016     2.101
                 2.12       0         .250       .005     2.101
                 4.13       0         .247       .053     2.101
                 6.15     .007        .246       .000     2.101
                 8.12     .205        .246       .000     2.101
                10.12     .583        .249      -.000     2.101
                12.18     .788        .256      -.001     2.101
                14.15     .840        .262       .000     2.101
                16.12     .617        .261      -.000     2.101
                18.20     .168        .249       .000     2.101


       DAY  1
       TOTAL DAILY RESPIRATION =  6.0809G/M**2
       TOTAL DAILY PHOTOSYNTHESIS =  6.4276G/M**2
       P/R RATIO = 1.0570
```

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COMPUTED VALUES OF SURFACE D. O. EXCHANGE (G/(M*M*HR)),
                   SURFACE EXCHANGE COEFFICIENT (/HR),
                   SATURATION D.O. CONCENTRATION (G/M**3),
                   AND WATER TEMPERATURE (DEG. C)
                   FOR EACH CHANNEL SEGMENT


SECTION NO.           6      7      8      9

     TIME = -4.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0122  .0062  .0214  .0075
SE COEFFICIENT     .0699  .0699  .0699  .0699
SAT. D.O. CONC.     8.99   8.99   8.99   8.98
TEMPERATURE        18.91  18.94  18.96  18.99

     TIME = -2.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0260  .0133  .0471  .0173
SE COEFFICIENT     .0697  .0697  .0697  .0699
SAT. D.O. CONC.     9.06   9.07   9.08   9.09
TEMPERATURE        18.58  18.53  18.48  18.43

     TIME =     0  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0363  .0172  .0600  .0216
SE COEFFICIENT     .0696  .0696  .0696  .0696
SAT. D.O. CONC.     9.17   9.18   9.19   9.20
TEMPERATURE        17.98  17.92  17.87  17.82

     TIME =  2.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0412  .0192  .0668  .0238
SE COEFFICIENT     .0696  .0695  .0695  .0695
SAT. D.O. CONC.     9.23   9.25   9.26   9.28
TEMPERATURE        17.66  17.59  17.51  17.44

     TIME =  4.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0436  .0202  .0701  .0250
SE COEFFICIENT     .0695  .0695  .0695  .0694
SAT. D.O. CONC.     9.28   9.30   9.32   9.34
TEMPERATURE        17.45  17.35  17.25  17.15

     TIME =  6.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0473  .0213  .0729  .0256
SE COEFFICIENT     .0698  .0698  .0698  .0694
SAT. D.O. CONC.     9.32   9.34   9.36   9.38
TEMPERATURE        17.25  17.15  17.05  16.95

     TIME =  8.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0439  .0186  .0625  .0216
SE COEFFICIENT     .0694  .0694  .0694  .0694
SAT. D.O. CONC.     9.34   9.36   9.38   9.40
TEMPERATURE        17.15  17.05  16.95  16.85

     TIME = 10.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0285  .0085  .0243  .0071
SE COEFFICIENT     .0694  .0694  .0694  .0694
SAT. D.O. CONC.     9.34   9.36   9.39   9.41
TEMPERATURE        17.14  17.01  16.89  16.76

     TIME = 12.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.      .0061 -.0048 -.0265 -.0127
SE COEFFICIENT     .0695  .0696  .0696  .0695
SAT. D.O. CONC.     9.32   9.30   9.29   9.27
TEMPERATURE        17.24  17.31  17.39  17.46

     TIME = 14.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.     -.0164 -.0155 -.0651 -.0272
SE COEFFICIENT     .0696  .0697  .0697  .0697
SAT. D.O. CONC.     9.22   9.18   9.14   9.09
TEMPERATURE        17.71  17.94  18.16  18.39

     TIME = 16.00  FLOW RATE =   .0128 (M**3/SEC)
SURFACE EXCH.     -.0225 -.0174 -.0722 -.0303
SE COEFFICIENT     .0699  .0699  .0700  .0715
SAT. D.O. CONC.     9.14   9.10   9.05   9.00
TEMPERATURE        18.13  18.38  18.62  18.88
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      TIME = 18.00  FLOW RATE =    .0128 (M**3/SEC)
SURFACE EXCH.    -.0082 -.0070 -.0326 -.0152
SE COEFFICIENT    .0725  .0725  .0725  .0746
SAT. D.O. CONC.    9.15   9.12   9.08   9.05
TEMPERATURE       18.09  18.26  18.44  18.61

      TIME = 20.00  FLOW RATE =    .0128 (M**3/SEC)
SURFACE EXCH.     .0152  .0066  .0181  .0047
SE COEFFICIENT    .0725  .0725  .0725  .0746
SAT. D.O. CONC.    9.21   9.22   9.23   9.24
TEMPERATURE       17.77  17.73  17.68  17.63
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TYPING GUIDE SHEET
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APPENDIX D

TOTAL, PARTICULATE AND DISSOLVED NITROGEN AND PHOSPHORUS CONCENTRATIONS AND CHLOROPHYLL-*a* CONCENTRATIONS IN CHANNEL 7 (by Taylor and Sheldon, 1981)

Date	Station Type	Total N (mg ℓ^{-1})	Particulate N (mg ℓ^{-1})	Dissolved N (mg ℓ^{-1})	Total P (μMℓ^{-1})	Particulate P (μMℓ^{-1})	Dissolved P (μMℓ^{-1})	Chlorophyll-*a* (μgℓ^{-1})
6-24-78	A	1.71	0.24	1.47	13.88	4.43	9.45	4.51
6-24-78	B	2.63	0.65	1.98	16.55	11.25	5.30	8.06
7-5-78	A	N.D.*	N.D.	N.D.	12.76	4.28	8.48	9.41
7-5-78	B	N.D	N.D.	N.D.	32.65	12.92	19.73	15.17

*N.D. = No data obtained.
Station A = upstream end of channel at entrance to riffle.
Station B = downstream end of channel at entrance to pool.

APPENDIX E

DAILY RATES OF PHOTOSYNTHESIS AND RESPIRATION FOR SUBCOMMUNITIES OF POOL 14 and RIFFLE 13 IN CHANNEL 7. ALSO GIVEN ARE DIEL CURVE ESTIMATES OF DAILY TOTAL POOL OR RIFFLE PHOTOSYNTHESIS AND RESPIRATION.* (Rates are in g O_2m^{-2} day^{-1}, by Taylor and Sheldon, 1981).

POOL 14

	Planktonic		Macrophytic + Epiphytic		Planktonic + Macrophytic + Epiphytic		Total Daily* (Diurnal O_2)	
Date	Photo.	Resp.	Photo.	Resp.	Photo.	Resp.	Photo.	Resp.
6/27/78	0.93	1.47	7.41	10.72	8.34	12.19	8.19	7.81
7/17/78	0.56	0.54	7.67	10.07	8.23	10.61	10.34	10.37
8/5/78	0.55	0.58	7.05	10.56	7.60	11.14	10.04	12.00
8/9/78	0.35	0.48	4.77	10.48	5.12	10.96	6.46	11.06
8/10/78	0.38	0.56	4.61	10.56	4.99	11.12	7.92	11.06
8/29/78	0.43	0.62	4.72	10.48	5.15	11.10	3.88	12.96
9/21/78	0.10	0.16	4.12	9.34	4.32	9.50	2.59	7.20
10/6/78	0.02	0.23	0.14	0.77	0.16	1.00	0.46	1.85
6/13/79	0.26	0.70	29.26	13.11	29.52	13.37	30.20	12.96

*Independent data collection and interpretation by a graphical Odum method.

APPENDIX E (Cont'd)

RIFFLE 13

Date	Planktonic		Benthic		Planktonic + Benthic		Total Daily*** (Diurnal O_2)		
	Photo.	Resp.	Photo.	Resp.	Photo.	Resp.	Photo.	Resp.	Photo. (w/Reaeration)
6/27/78	N.D.*		N.D.		N.D.		N.D.		
7/17/78	N.D.		N.D.		N.D.		N.D.		
8/5/78	0.33	0.58	10.83	9.72	11.16	10.30	8.33	12.03	11.81
8/9/78	0.34	0.48	10.16	8.43	10.50	8.91	7.15	9.12	9.83
8/10/78	0.34	0.56	10.27	9.80	10.61	10.36	9.06	10.80	11.89
8/29/78	0.25	0.62	8.36	11.41	8.61	12.03	5.51	6.0**	6.22
9/21/78	0.15	0.16	1.47	4.50	1.62	4.66	2.66	5.76	2.66
10/6/78	0.04	0.23	0.80	1.57	0.84	1.80	2.48	2.88	2.48
6/13/79	0.24	0.35	3.32	11.87	3.56	12.22	3.88	12.31	3.97

*N.D. = No data obtained.

**The riffle respiration estimates of 8/29/78 were possibly affected by a brief heavy rain which fell just at dusk.

***Independent data collection and interpretation by a graphical Odum method.